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GEOLOGICAL MAGAZINE

VOL. XCVII, No. 3. PUBLISHED 22.6.1960 MAY–JUNE 1960

The Efficacy of Natural Selection as an Evolutionary Agent, with Particular Reference to the Fossil Record

By F. H. T. RHODES

ABSTRACT

The recent suggestion that natural selection of random mutations is inadequate to account for the major features of evolution is rejected. The pattern of evolutionary development in most major groups, the phenomena of extinction and replacement, the rates of appearance of new major taxa, the continuing vitality of the evolutionary process, the overall randomness of evolutionary history, containing directional change within individual lineages, the nature of natural selection, and the geologic evidence for environmental instability are examined. All suggest that natural selection and random variation are adequate to account for the major features of evolutionary history.

I. INTRODUCTION

PROFESSOR JAMES BROUGH'S recent article on *Time and Evolution* (1958) raises a number of problems which are of common interest to all students of evolution, but particularly to palaeontologists.

After a most stimulating discussion Brough concludes that the Neo-Darwinian concept of natural selection acting upon random mutations is inadequate to account for the major features of evolutionary history, although he recognizes the action of natural selection as an effective factor in evolution at low taxonomic levels. He suggests that a more probable explanation of major structural change in the past is the former existence of " directional mutations occurring at a very high rate " (1958, p. 24).

Brough's article is therefore essentially a challenge to what has now become evolutionary orthodoxy. " There are certain facts," he writes (p. 17), " which have not been adequately explained. . . . The Neo-Darwinians may find explanations for them; if so very well; but if not these facts should not simply be ignored, and if a theory of another kind can explain them better, it should be given consideration."

It is the purpose of the present article to review these facts in the light of the fossil record.

II. EVOLUTIONARY RATES AND PATTERNS

(*a*) *The Pattern of Variation in Evolutionary Rates*

Both the absolute and the relative speeds of evolution have varied, not only in different groups but also at different times with the same

group. Brough believes that three rates of evolutionary change may be distinguished (1958, p. 17):—

(1) " a more or less steady rate . . . [which] seems to affect only smaller systematic changes—specific, generic or familial ". E.g., horses.

(2) " evolutionary change [which is] markedly uneven in time, a relatively very rapid early evolution which produced large systematic changes of ordinal or class status being followed by a long period of relative stagnation when the lines were affected by only minor evolutionary changes ". E.g., Dipnoi, Coelacanthi, and Chelonia.

(3) " so called ' explosive points ' in evolution, when in a relatively short time great evolutionary changes are carried out and several new groups appear, all of high systematic status ". E.g., Eocene mammals.

These three rates of evolution are frequently displayed at successive periods within the history of a single group. Can this sequence of evolutionary phases be adequately explained on the basis of natural selection acting on random mutations, or does it, as Brough suggests, demand the existence of " directional mutations occurring at a very high rate " ? (Brough, 1958, p. 24).

Three factors need to be considered. Firstly, the explosive phase of evolutionary activity does not commonly occur at the first appearance of the group. Fish first appear as fossils in strata of Middle Ordovician age. They exhibit " explosive " evolution in Devonian time—some seventy million years later. Mammals first appear in the Middle Jurassic; they undergo " explosive " evolution in Paleocene times, some eighty million years later. The same " lag " is seen in many other groups, and there is a comparable delay between the peak in rate of origin of orders and that of families and between that of families and genera. Such a sequence does not suggest that the rate of development is chiefly controlled by relatively higher mutation rates, for if these were the chief factor there appears no obvious reason for such consistent time lags in the appearance of most taxa. These are readily explicable, however, in terms of natural selection, as we shall later see.

Secondly, the " explosive " phase of the development of any group often involves the replacement (sometimes delayed) of another group occupying the same environment. This is well illustrated by the replacement of amphibia by reptiles, reptiles by mammals, Triassic by Jurassic ammonite groups, and Agnatha by higher fish. This strongly suggests that reduction or absence of competition by the availability of new environments is a major factor in such change. Thirdly, there is one other aspect of evolution common to all groups—that of extinction (or zero evolutionary rate), and any

consideration of the evolutionary process must give prominence to this. It is always tempting to attempt to correlate the extinction of a fossil group with what were the prevailing physical conditions of the time—and the correlation is often misleading. Yet having said this, it is difficult to escape the conclusion that such mass extinction as that which took place in the Permian was a reflection of extreme Permian environments. The widespread glaciation in the southern hemisphere, with high emergent continents, late Palaeozoic orogeny in many areas, the spread of reefs, red beds and evaporites, and the great restiction of late Permian seas seem to have formed a combination of features which exercised a profound, though intensely complex and varied, series of effects upon Upper Palaeozoic life.

If we accept this general sequence of evolutionary rates for any group, we can express them also in terms of the organism-environment relationship. Thus after the appearance of a new group the "explosive" evolutionary rate may be said to correspond to the invasion of new environments, the "uneven" phase to the fuller exploitation of various ways of life within those broad environments, and the "steady" phase to continuing consolidation and adaptation. There is nothing here which suggests that natural selection is not the primary agent in such development.

(*b*) *An Analysis of the First Appearance of Major Taxa* (*Classes, Orders, Families*)

Brough writes: "It . . . seems likely that all the phyla were already in existence in the Cambrian with the possible exception of the chordates and that in the vast period of time that has elapsed since then no new phyla have been evolved" (Brough, 1958, p. 27). "Since no new phylum has appeared in over 500 million years it would seem unlikely that any will appear in the future" (p. 28).

"In many well documented phyla, class evolution which had characterized their history before, characterizes it no longer, and in the long period since the Carboniferous no new classes have appeared . . . (except for the birds and mammals). . . . In view of this it would seem unlikely that any could now appear."

"When we consider the evolution of orders, the same story is repeated to rather a surprising degree in some cases but here another factor appears to enter which will be seen if we consider aquatic and terrestrial forms separately. If we take the aquatic phyla, the Echinodermata, Coelenterata, Porifera, and Molluscoidea and the mainly aquatic phylum the Mollusca . . . the total number [of orders known as fossils] is forty-seven. Of these forty were in existence in the lower Palaeozoic, three more appear in the Devonian, and four appear sporadically in the Mesozoic. . . . In the Coelenterata and the

Molluscoidea no new orders have appeared since the Ordovician" (Brough, 1958, p. 29). [All figures based on Zittel, 1913]. . . . "The phyla which include large numbers of terrestrial forms are somewhat different, but the difference is not a fundamental one, the underlying pattern being the same" (Brough, 1958, p. 30). ". . . the evidence as far as it goes shows, particularly in aquatic forms, that the production of new families has declined" (Brough, 1958, p. 31).

In general these statements are correct in kind but not in degree, for the use of figures based upon taxonomy which is almost half a century old gives a somewhat misleading impression of the extent of the decline in the appearance of new taxa. Thus the statement that "in the Coelenterata and the Molluscoidea no new orders have appeared since the Ordovician" (Brough, 1958, p. 29) is no longer true. Part F of the *Treatise on Invertebrate Paleontology*, a work by ten specialists devoted entirely to the Coelenterata, lists the numbers of orders appearing at various times as: PreCambrian 1, Cambrian 6, Ordovician 3, Silurian 1, Carboniferous 1, Permian 1, Triassic 2, Jurassic 4, Cretaceous 3, Tertiary 1, Recent 6. This represents a total of 21 new coelenterate orders in post-Cambrian times.

It may be argued that the tendency of all modern taxonomy is towards "splitting" rather than "lumping", but this is to miss the point. Once any count of taxa is made, it is essential to use the best available data. Taxonomic differentiation reflects similarities and differences between organisms, and there will be just as much splitting in modern work on, say, Cambrian faunas, as there is in those from the Cenozoic. Whether there is any real basis for regarding the "taxonomic value" of a class within, say, the Bryozoa as comparable with a class within the Chordata is debatable—but it remains debatable whatever degree of taxonomic refinement is used as a basis for comparison. The study of many invertebrate groups (e.g. the Foraminifera) had scarcely begun fifty years ago.

Much the same case may be made for the other examples which Brough quotes. The general decline which he describes is a fact; in degree, however, the decline is far less dramatic than he implies.

Now if we accept this decline in the development of new major taxa certain considerations arise, to which we must now turn.

(*c*) *Absolute Rates of Evolution*

To compare the Palaeozoic, Mesozoic, and Cenozoic as though they were broadly similar time units gives a quite misleading impression. The Palaeozoic era covered a span of at least 335 million years, and probably as much as 500 million years (Mayne, Lambert, and York, 1959, p. 212). The Mesozoic era, however, represents a period of only 125 million years, and the Cenozoic era 60 million

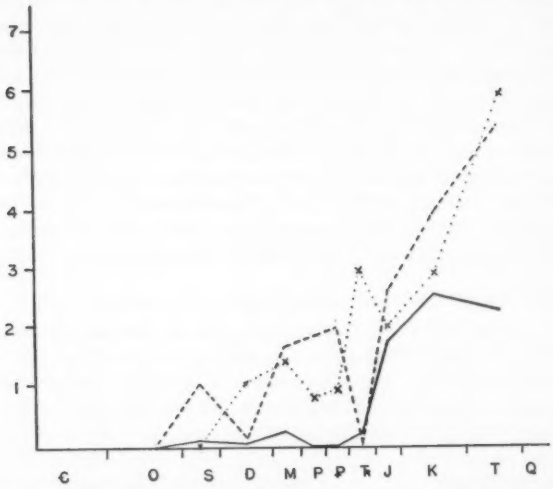
years (Holme's scale). The Palaeozoic era, therefore, is almost twice as long as the Mesozoic and Cenozoic combined. Brough rightly indicates the hazards of measuring evolutionary rates in absolute periods of time (see also George, 1958, and Williams, 1957), but in spite of the hazards it is a useful exercise. Thus, for example, even if one accepts the lesser estimate for the duration of Palaeozoic time, the first appearance of nine coelenterate orders in the 160 million years of Cambro-Ordovician time (Holme's scale) represents an average of 17·7 million years per new order, while the post-Ordovician first appearances of 18 orders in 360 million years represent an average period of 20 million years per new order. There is little substantial difference between these two figures, nor, in spite of the discrepancies between the two scales, is there any substantial difference between the corresponding figures of 24·4 million years and 30 million years per new order measured on the Mayne, Lambert, and York scale.

Again the decline in the appearance of new forms remains a fact: but it is far less extensive than Professor Brough suggests.

(*d*) *The Apparent Cessation of the Evolutionary Process*

Brough writes: " . . . If the general pattern outlined above means anything, it means that evolution is almost or quite spent as a major creative force " (p. 37). This point of view is common among neontologists, but the decline in development of major taxa does not necessarily imply a decline in evolutionary impetus. On the contrary, it often marks periods of very considerable differentiation at lower taxonomic levels. Text-fig. 1 shows a plot of the numbers of new genera per million years for bony fish, echinoids, and foraminifera. These three groups are at an all-time peak of generic differentiation, in spite of the fact that there have been no new class appearances of fish since the Devonian, no new orders of echinoids since the Jurassic, and no new super-families of foraminifera (other than the Allo gromiidae) since the Jurassic. Brough observes: " the overall picture given by these aquatic phyla is impressive; almost no evolution of major units has occurred since about the middle of the Palaeozoic. Can evolution in these groups be said to have lost its impetus by that time ? " (1958, p. 30). The answer must surely be a qualified " no ", for what the graphs of Text-fig. 1 indicate is rather a replacement of the original " explosive " evolutionary phase by the more stable phase of development of new genera. And the important point to note is that this succession of evolutionary activity, which is so typical of the history of individual groups, appears to be no less typical of the whole evolutionary process. Throughout the organic world, evolution has had an evolution ! This is a key factor to which we shall later return.

The final fact to be recognized is that a decline in the production rate of new major taxa is no new feature in the history of life. Text-fig. 2 shows clearly that if an observer living in Silurian or Permian times had studied the rate of appearance of new taxa, he might have concluded, with every bit as much justification as a present-day observer, that evolution was " almost or quite spent as a major



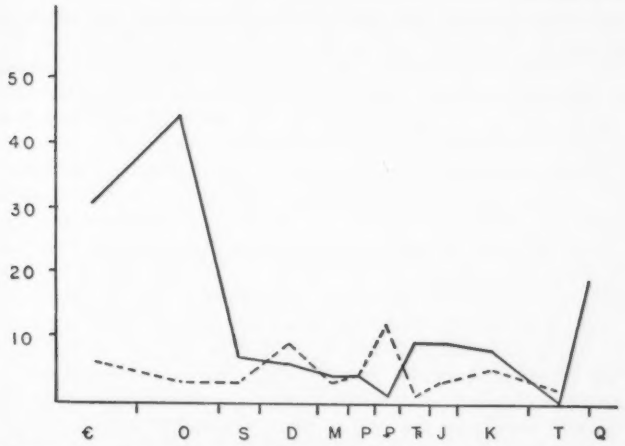
TEXT-FIG. 1.—Graph showing numbers of new genera per million years (plotted on vertical axis) through geological time for Foraminifera (continuous line), Echinoidea (broken line), and Osteichthyes (dotted line with crosses). Data from Newell, 1952.

creative force ". But his conclusion would have been incorrect. The future of evolution remains as unpredictable now as it was then.

Certainly, however, this decline can scarcely be regarded as the end of the evolutionary line. Brough claims that " . . . the only certain fact known to us . . . is that in the last few thousand years no recognizable evolution seems to have taken place " (Brough, 1958, p. 18), and concludes: " We can be quite clear therefore, that some factor or factors influencing this evolutionary process have changed " (p. 20). The recent description of industrial melanism (Kettlewell, 1955) in which the formerly very rare black form of the Peppered Moth, *Biston betularia*, has replaced the typical lighter form in an air-polluted industrial area at Rubery, Birmingham, is a most striking testimony both to the continuing vitality of the evolutionary process and the effectiveness of natural selection. Kettlewell's statistical

demonstration of predation rates of these moths by various birds is a superb example of natural selection in action.

It must always be borne in mind that the absolute speed of evolution is so slow that major morphological change is scarcely perceptible at our normal levels of observation. Simpson has shown, for example, that in the early period of equid evolution the rate of change of



TEXT-FIG. 2.—Times of appearance and extinction of various classes and orders of aquatic invertebrates plotted against Holme's scale of time.

Times of appearance (continuous line) and extinction (broken line) of taxa are not subdivided below the level of periods. All are plotted at mid-points of their respective periods.

Worms and insects are omitted.

Classes are included only in the case of such comparatively rare groups as pleosponges, receptaculitids, edrioasteroids, paracrinoids, etc., which are not generally classified below the class level and would not therefore be represented by orders. The taxonomy is based on that given by Moore, Lalicker, and Fischer, 1952, *Invertebrate Fossils*.

The first appearance of a number of taxa in recent times may be the result of their lack of hard parts and may not necessarily imply no prior existence.

Where an order is confined to a particular period, both its appearance and extinction are counted in the totals for that period.

diameter in molar teeth was of the order of 0·2 mm. per million years, while differences of 3·0 mm. were present in single populations.

(*e*) *The Random Overall Pattern of the Evolutionary Process*

One of the major features of the fossil record on which Brough bases his suggestion of directional mutations is the apparently

non-random character of evolutionary change. Thus he writes: " The evolutionary surges which characterize certain phases of the history of animal groups are not random. The mutations are additive and leading to definite ends. . . . Since these mutations were progressive, each going a step further in definite process, they were not random in character but belonged to a chain which would produce one result and no other " (Brough, 1958, p. 23).

Brough quotes as examples of these non-random changes " the complete replacement of the jaw mechanism in the mammal-like reptiles, the complete breakdown of the bony cheek of ancestral forms in the actinopterygian fishes, and the steady reduction of the scale lobe of the tail; and the production of a new and effective limb type in the evolution of the tetrapods " (p. 23).

There are two separate questions involved here. Firstly, is the course of evolution random and, secondly, if it is random, does randomness necessarily imply the existence of directional mutations? It is important here to emphasize that this discussion is concerned only with the immediate mechanism of evolution and does not involve the teleological aspect of its course. Randomness may be defined as " lacking definite direction, orientation, or regularity ". In one sense the course of evolution is random, in another it is not. In an overall view evolution is entirely random—there are no constant trends or continuous features—no obvious overall plan, orientation, or direction. Certainly there are a few general characteristics (the invasion of new environments, the general increase in total numbers of living things, and so on) but there is still " an odd randomness in it, a sense that it is dominated by a sort of insensate opportunism " (Simpson, 1950, p. 121). If there is any *overall* direction or trend in the course of evolution, it has yet to be described.

But within the great framework of total evolutionary change, not all is random. There are places in the record where the development of certain groups is rigidly directional. These are represented, for example, by the cases which Brough quotes. This directional change is not a universal feature; it is both less common and less complete than is frequently implied, but it does exist. It is much less common at higher levels, however, than was once supposed. In the classic example of " straight-line " evolution, for example, Simpson (1951, p. 206) concludes that " evolution of the horse family was definitely not orthogenetic. . . . There was, for instance, no constant and overall increase in size. The feet did not steadily change from four toes to three and then to one. . . . And so it goes for all the changes that have occurred in the history of the family; not one of them shows the constant guided change in single direction that is demanded of the theory of orthogenesis ".

There is one other sense in which evolution is not random, just as the history of mankind is not random, for as we now look back in retrospect we observe that it has taken such and such a course. And if it has taken such and such a course it is, by definition, not random. Yet this does not imply that there were not other theoretically possible directions of development which might have occurred. Brough's suggestion that mutations in Waagen's sense " were not random in character but belonged to a chain which would produce one result and no other " is true, in retrospect, but it does not necessarily indicate that no other evolutionary course *could* have been followed.

Secondly, does the presence of such directional evolution as there is, necessarily imply the existence of directional mutations ? To answer this question we must consider the nature of natural selection.

III. Natural Selection

(*a*) *Its Nature*

One of the clearest definitions of natural selection is that given by Darwin himself (1872, p. 74): " If such variations do occur, can we doubt (remembering that many more individuals are born than can possibly survive) that individuals having any advantage, however slight, over others, would have the best chance of surviving and procreating their kind ? . . . This preservation of favourable individual differences and variations, and the destruction of those which are injurious, I have called Natural Selection."

The effect of natural selection is at once clear—it is to produce " non-random reproduction ". In one sense, therefore, the more intense the selection pressure, the more non-random or rigidly undirectional will be the evolutionary response. Far from disproving the action of natural selection, the partial non-random character of the evolutionary process strongly supports it.

Does this then imply that the whole fabric of evolutionary development should be non-random ? It does not, for natural selection is not the only factor involved in the evolutionary process, and there are obvious limits to its range of effectiveness because it can act only upon differences which already exist within the range of environments available. It is this that gives to the total fabric of evolutionary development its sense of " insensate opportunism ", for the final direction and extent of development are the result of an intricate combination of constitutional, physical, and environmental factors.

(*b*) " *Positive and Negative* " *Effects of Natural Selection*

Brough writes: " Natural selection may play a part as a positive agent in evolution but only under certain conditions. During the

evolutionary surges Natural Selection is pushed aside except as a negative force. . . . If these populations can make a living and reproduce adequately they will persist, if not they will become extinct, Natural Selection acting here but only in a negative sense. . . . These surging phases of evolution . . . are followed by . . . extensive speciation and adaptation [in which] . . . Natural Selection may play its role as a positive factor " (p. 25).

It is difficult to distinguish between the " positive " and " negative " effects of natural selection in this sense, for there is no obvious difference between Brough's description of its " negative " effect in " evolutionary surges " and its effect in any other type of evolutionary development. It is always " negative " in the sense that it can act only on variations available within given environments. But there is also a sense in which whenever and wherever it acts it is positive or creative in that it has radical effects upon the gene pool of given populations, moulding " the separate units of heredity into a co-ordinated whole, a process as truly creative . . . as the combination of separate bricks into a building ", as Simpson, Pittendrigh, and Tiffany remark. The notion of natural selection as a negative process, able to account for the " elimination of the unfit but not for the origin of the fit " could apply only so long as natural selection was regarded as the survival of the fittest through the struggle for existence. Once it is seen as promoting non-random reproduction, it becomes a positive (as well as a negative) evolutionary factor.

(*c*) *Geological Evidence for Environmental Instability*

One of the key factors in Brough's argument against the efficacy of natural selection is his conclusion that there is no evidence for environmental instability during the development of certain groups. He writes: " There are . . . cases in which a rapid evolutionary outburst produces orders and classes and in which it is very difficult to picture environmental instability as an active factor. . . . What evidence there is seems to suggest that in this type of evolution the environment played no positive role " (Brough, 1958, pp. 20–21). Brough gives as an example the Permo-Triassic development of the higher orders of the actinoptyergian fish, and after discussing the evolution of the ptycholepid fishes during Triassic and Lower Jurassic time, he concludes: " Now these large structural changes may or may not have been useful in themselves, but there is nothing whatever to suggest that they had anything to do with environmental instability. On the contrary the evidence suggests environmental stability throughout . . . with regard to environment, the evidence suggests that in large-scale evolution environmental instability seems to have played no part " (pp. 21–22).

Now it seems to me that this conclusion is at variance with the findings of modern geology. Every change in grain size in sedimentary rocks, every mineralogical variation, every textural difference, every irregularity of bedding, every minute variation in carbon, or sulphur or trace-element content—all these are firm evidence of environmental instability, often of a very radical kind. Virtually every sedimentary sequence examined is full of them, and even the most superficially homogeneous sequence of, let us say, black shale, may, on detailed analysis, yield evidence of considerable instability in its depositional environment. Eager's demonstration (1951) of the correlation between decrease in the number of fossil nonmarine pelecypod shells per unit thickness of sediment, decrease in their mean size, and slight change in their relative growth rates with decrease in percentage of carbonaceous matter in the Coal Measure sediments in which they occur, is an example of such environmental variation. Broadhurst (1959) in a detailed analysis of a section of Coal Measure strata only 40 inches in thickness has shown the shell size of nonmarine pelecypods to be directly related to the organic carbon and detrital quartz content of the sediments, and inversely related to their macroscopic pyrite content, and has concluded that at least five distinct environmental episodes are represented. Carozzi and Zadnik's (1959) study of the microfacies of superficially homogeneous vertical sections of strata from the Silurian Wabash reef of Indiana shows changes in both lithology and organic content which imply substantial environmental changes in time, mostly associated with variation in depth.

The very existence of the fossil record at all is a monumental testimony to the continuing environmental instability of the earth. If examined in detail over anything more than a geologically infinitesimally small period of time, no depositional environment, no sedimentary sequence, no portion of earth history gives evidence to the contrary.

(*d*) *Environmental Instability and Natural Selection*

This is not, of course, to deny that there may be limited periods of environmental stability or somewhat longer periods of essential stability within some environments. In the absence of any detailed examination it might be claimed that the mid-water plankton-feeding habit and environment of the ptycholepid fishes was substantially unchanged from Lower Triassic to Lower Liassic times, as Brough claims, though many geologists would doubt such environmental stability. Even in such possible cases as this, however, there is no reason to suppose that natural selection becomes inoperative as an evolutionary factor. The increasing perfection of adaptation

of a relatively poorly adapted (if surviving) group of organisms in a stable environment may produce morphological changes just as readily as selection in a changing environment.

(*e*) *The Recognition of Adaptive Changes*

Professor Brough appears to suggest that some changes in certain groups are non-adaptive. Thus, he writes: "In the several chondrostean lines which were affected by the changes which eventually produced the higher orders there were fishes of many kinds . . . clearly indicating a number of quite different habits and habitats. Yet all were affected at about the same time by the greater changes of fins and skull which produced the higher orders. So, so far from these . . . changes being caused by environmental instability they seem to have triumphed over it, and swept through the actinopterygian fishes regardless of environmental conditions." "This story is repeated in the mammal like reptiles where the significant changes which among other things replace the reptilian jaw apparatus by that of the mammal were carried out in several distinct orders which were apparently adapted to a variety of environments. Any idea of the new jaw apparatus being an adaptation to a particular environment clearly does not apply" (1958, p. 22).

Yet the superiority of the mammalian to the reptilian jaw in strength, versatility, and in the modification of some earlier reptilian parts (the quadrate and articular bones) is such that there is little reason to suppose that it was an adaptation to a *particular* environment. Indeed, it is difficult to imagine any environment in which its superiority would not be a considerable advantage.

This general adaptation is the clue to parallel evolution and the less common feature of convergence. In parallel evolution, where the groups concerned are usually more or less closely related, broadly similar changes arise as a result of natural selection acting upon some of the similar mutations which occur, but there seems no justification for supposing that such similar mutations are directed, particularly in view of the fact that parallelism never involves exactly similar changes and seldom takes place at exactly the same period of time. In such related groups, however, the total range of mutations may well be broadly similar.

The case of convergence offers even more striking support for the efficacy of natural selection. The overall resemblance between humming birds and humming moths is so striking as to be almost unbelievable when first seen, but it seems scarcely reasonable to suggest that the same directed mutation occurred in two such distinct groups. The most significant feature of their structural similarity is their

similarity of habits. It is this that gives strength to the acceptance of natural selection acting upon random mutations as the dominant evolutionary agent.

The biggest difficulty in the acceptance of this argument in other cases is that of the recognition of adaptive change. In most cases specific differences are clearly adaptive, although rarer differences which appear either non-adaptive or are not obviously adaptive also exist. Many specific differences are " obviously " adaptive (as in Darwin's finches) but such other factors as the general correlation of habits and related structure, the ecological habit and habitat distinctiveness of most similar species in a given region (especially terrestrial vertebrates), the several graded geographic variations in characters and their correlation with environmental factors (all quoted by Simpson, 1953, p. 168) are good reasons for accepting the generally adaptive nature of differences represented by lower taxonomic categories. At higher taxonomic levels the evidence for nonadaptive differentiation is very much weaker (see Simpson, 1953, pp. 177–9, for a detailed discussion)—so much so that some neontologists would regard such nonadaptive differences as wholely absent.

With regard to the rarer differences between related sympatric species which cannot obviously be interpreted as adaptive in character, two points need to be considered. One is the difficulty of recognizing as adaptive certain changes which are (quite apart from our recognition) in fact adaptive. This is especially true in the early stages of adaptation. Secondly, differences between taxa may or may not be adaptive. To claim that such and such a difference between two groups appears nonadaptive may be valid—but it may be quite irrelevant to the question of the efficacy of natural selection. Natural selection can act only on mutations which are " provided " by the organisms—and differences may simply reflect differences in the total genetic data on which selection operated. This may well account for many examples of " nonadaptive differences ".

Perhaps one of the strongest indications that major taxonomic differentiation did not involve overall directional or correlated mutation is provided by de Beer's elegant demonstration of mosaic evolution in vertebrate evolution (1954).

IV. The Evolution of Evolution

There remains the problem of the pattern of evolutionary development to which reference has already been made (p. 177). It has been shown that it is too simple and too radical to suggest that " evolution has lost its impetus " but that it is true that there has been a decline in rate of appearance of major taxa (phyla and classes). Brough

concludes from this that " some factor or factors must have been operating which ceased to operate subsequently or operated in a much modified form " (p. 23). It seems to me, however, that the action of natural selection on random mutations will inevitably tend to produce the pattern which we have discussed. For just as the origin of life almost certainly removed once and for all from the earth the physical conditions in which such " spontaneous generation " could take place (Rhodes, in press), so the development and initial deployment of life removed once and for all the conditions under which such rapid differentiation could take place on such a large scale. The initial rapid development of major taxa must surely be correlated with the widespread availability of empty environments and niches. It is this that provides the explanation for Brough's observations on the developmental difference between the aquatic and nonaquatic groups (p. 30). Once the major aquatic phyla and classes were established, the " bases were loaded ", the main themes and patterns of the aquatic ecological economy were established, and further major development could occur only by replacement of groups which, because of their adaptation, were not rapidly or easily to be replaced. Once some did become extinct, as in Late Permian and Cretaceous time, they were rapidly replaced by new groups—in other words, there was a rapid increase in evolutionary rates for major taxa. The case of the land is slightly different in the beginning of organic divergence but not in its development. For life on the land (and flight in the air and so on) present new and (anthropomorphically) much greater problems than life in the water, which demanded (again anthropomorphically) a level of organic construction and complexity and a means of life (terrestrial food supplies, for example) that took longer to develop. Yet once they did develop the story is precisely similar; the major evolutionary changes took place as a result of either (*a*) the invasion of new environments (as by the amphibia), (*b*) the (broadly similar) more extensive colonization of only partly utilized environments (as by the reptiles on the land), or (*c*) the extinction and consequent replacement of groups occupying the same ecological areas (mammalian replacement of reptiles, for example). These are all readily explicable as the result of natural selection, and there appears to be no valid reason for supposing that periods of major evolutionary change require the invocation of other factors. This is not, of course, to disprove that such other factors as directional mutation conceivably may have played some part in the process, but it is to suggest that this is unlikely. Natural selection is an observed factor in living populations. Random mutation is an observed fact in living populations. Directional mutations are not, and there seems no obvious support for them within the fossil record.

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Spilitic Rocks in South-east Devonshire

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Abstract

Volcanism began in South-east Devonshire with the extrusion of keratophyric tuffs in the Lower Devonian. The majority of extru ves in the Middle and Upper Devonian are basic spilites but there are intermediate varieties. Volcanism in the Middle Devonian was local and in the Ashprington area appears to have been continuous throughout the epoch. At the beginning of the Upper Devonian keratophyric crystal and vitric tuffs were extruded in the Dartington area. Later in the Upper Devonian the Chipley pillow lavas were extruded: it is shown that these lavas were widespread and may probably be correlated with similar lavas at Pentire Head in North Cornwall. The final phase of volcanism is represented by the intrusion of swarms of sill-like bodies of spilitic dolerites in Upper Carboniferous times. Intrusive and extrusive rocks are distinguished, mapped, and classified petrographically.

Introduction

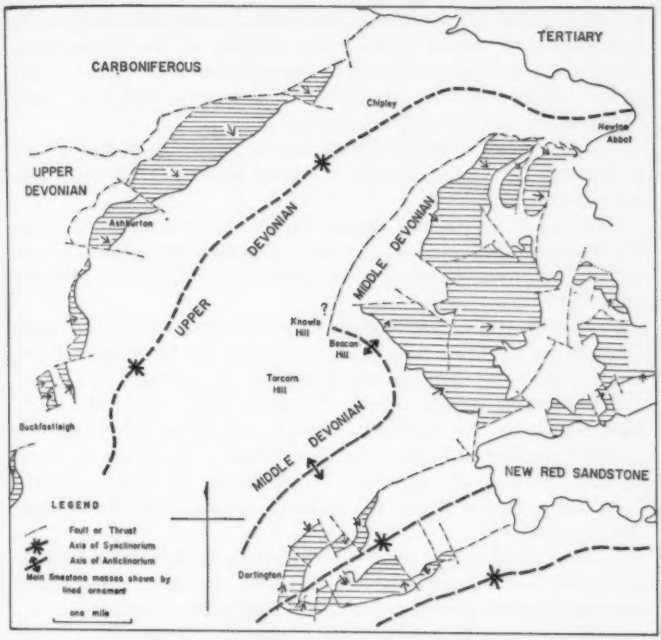
Extrusive volcanic rocks of Middle and Upper Devonian age occur in South Devonshire, where they are associated with a series of doleritic sills or laccoliths of Late Carboniferous age. The rocks have been described in part by Flett for the Geological Survey (cf. Ussher, 1903, 1912, 1913) and by Shannon (1922, and in Ussher, 1933), but no map showing clearly the distribution of the different types has hitherto been published, nor has there been a clear distinction made between extrusive and intrusive rocks.

The area is complex structurally, being one in which thrusting and overfolding to the north or north-east are developed as a result of the Variscan (Late Carboniferous) orogeny. Exposures are few with the result that exact stratigraphic relationships are doubtful in places. The purpose of this paper is to complete the petrographic description and to show the distribution of the various volcanic rocks in space and time, and to draw comparisons between the succession in S. Devon and N. Cornwall, and that in the Lahn and Dill areas of Germany.

Stratigraphy

The stratigraphy of the Newton Abbot area in South Devon, is shown in Table 1. This succession is based upon detailed mapping and study of the tetracoral and goniatite faunas of the limestones and shales with which the volcanic rocks are associated.

The volcanic rocks of the area were described in part by Champernowne (1889), who introduced the term Ashprington Series for the Middle and Upper Devonian volcanic rocks south of Totnes, just to the south of the Newton Abbot area. The rocks to be described may therefore be considered to belong to the same general phase of volcanic



TEXT-FIG. 1.—This map shows the simplified geology of the Newton Abbot area. From north-west to south-east the main structures are as follows : the Carboniferous (Culm) lies below a major thrust. This thrust truncates the Ashburton limestone (Middle-Upper Devonian) to the north-east. A branch of this thrust must also extend along the north-west margin of the Ashburton limestone since the shales on the north-west are Upper, not Middle Devonian. Further to the south, near Buckfastleigh, the Ashburton limestone thins considerably. A major synclinorium of Upper Devonian volcanic rocks and grey and red-and-green slates extends from east of Buckfastleigh to Newton Abbot. The south-east limb of this synclinorium is nowhere clearly defined since to the north it is thrust out, and to the south (north-west of Dartington) the Middle Devonian limestones have disappeared and are replaced by a monotonous grey shale sequence, with occasional lenses of limestone. The anticlinorium north of Dartington may not swing around in the manner shown : however, it is clear that the slates and volcanic rocks near Beacon Hill dip below the limestones to the north-east and belong to the Middle Devonian. The masses of limestones south-west of Newton Abbot dip mainly to the east at low angles, and are cut by numerous faults and thrusts. The most important of these extends from the north limb of the Dartington synclinorium, northwards towards Newton Abbot. In the area south-west of Newton Abbot there are two limestone formations, the lower being mainly a crinoid calcarenite or biostrome (Middle Devonian) and the upper being a pure biohermal stromatoporoidal limestone (Upper Devonian). In some areas the two limestones are separated by tuffs, but in other areas the lower limestone passes directly into the upper. In the Dartington area, only the lower limestone is present, and is overlain by dark grey shales with interbeds of crystal and vitric keratophyric tuffs.

activity, and the term " Ashprington Series ", never clearly defined by Champernowne, might perhaps be modified as the " Asprington Province " to indicate an area, in the general vicinity of the River Dart valley, which was the locus of volcanic activity from the Lower Devonian to the Upper Carboniferous.

The distribution of the various extrusive and intrusive rocks is shown in Text-fig. 2. Stratigraphically the rocks may be divided into four main groups, as follows:—

(1) The igneous rocks of Beacon Hill, which underlie the Givetian limestones of Torbryan. They consist of porphyritic spilitic andesite lavas (possibly also including some intrusive rocks), and are probably Upper Convinian in age.

(2) The Dartington keratophyric tuffs, which can now be accurately dated by the discovery of a goniatite fauna in the interbedded slates, as Lower Frasnian in age (probably zone 1α of Wedekind, 1918).

The following species were kindly determined by Mr. W. H. C. Ramsbottom of the Geological Survey and Museum: *Tornoceras simplex* (von Buch); *T. undulatum* (Sandberger); *T.* sp.; *Gephyroceras* sp. cf. *G. planorbis* (Sandberger); *G. planorbis*? The specimens were found in a quarry above the railway, in Staverton Wood, near Dartington.

In the western part of the area the Dartington tuffs are not found, but spilitic and keratophyric tuffs and lavas are developed at about the same horizon, directly overlying the Ashburton limestone.

(3) The Chipley lavas, which are intercalated in grey slates above the Ashburton limestone (and above the equivalents of the Dartington tuffs), but below the purple-and-green slates with *Entomis serratostriata* (Sandberger).

The Chipley lavas were probably extruded at a time of widespread volcanic activity throughout S.W. England, and may be tentatively correlated with the petrographically similar vesicular spilites of Pentire Head in North Cornwall. The succession at Pentire Head (cf. Dewey, 1914) is similar to that near Ashburton: in both cases pillow lavas are found in grey slates overlying Upper Devonian limestones (silicified in North Cornwall) and underlying purple-and-green slates with *Entomis*. Purple-and-green slates are widespread at the top of the Devonian throughout Devon and Cornwall (and also in other parts of Europe, as far east as Poland) and north of the Newton Abbot area, at Chudleigh, they may be accurately dated as younger than the *Clymenia* (*Laevigites*) limestones (i.e., zone V of Wedekind, cf. Anniss, 1933). The Pentire Head lavas overlie grey shales containing goniatites characteristic of Wedekind's zone II (*Cheiloceras*-Stufe or Nehden-Stufe cf. Dewey, 1914) and hence the Chipley–Pentire Head lavas may be roughly dated as zones III or IV (Hemberg-Stufe).

TABLE 1.—STRATIGRAPHIC SUCCESSION IN THE NEWTON ABBOT AREA

Period			Zone	Ashburton Area	Area south of Newton Abbot	Dartington Area
Upper Devonian	Upper (Fammenian)		VI V IV III II	Purple and green slates with ostracods Chipley lavas	Grey or buff slates Thin limestone Grey or buff slates with ostracods	
	Lower (Frasnian)		δ γ I β α	Spilite and keratophyre Ashburton limestone	Biohermal limestone	Top not seen Limestone Dark grey slates
Middle Devonian	Upper	Givetian	Dy	Base not seen	Keratophyric tuffs (Dartington tuffs) Biostromal and clastic limestones	Dark grey slates Biostromal and clastic limestones
	Middle	Givetian	Sp St			
		Couvinian	L		Limestone Fossiliferous slate	Slate Limestone Tuff
	Lower	Couvinian			Spilitic andesite	Fossiliferous slate

(4) The dolerite intrusions, which are of Upper Carboniferous age (see below).

Champernowne (1889), Ussher (1903), and Taylor (1952) have shown that, within the main Ashprington centre to the south, vulcanicity also took place at the end of the Middle Devonian, and may have been continuous throughout the Middle Devonian, being thus contemporaneous with the deposition of limestones in the Newton Abbot area.

Petrology

Introduction.—All the rocks to be described are included within the Spilitic Suite as defined by Dewey and Flett (1911). Many are fresh and unsheared, but the majority show clearly the effects of the Variscan (Hercynian) orogeny. Ussher used the term " Schalstein " to describe sheared basic rocks, whether lavas, pyroclastics, or intrusions. There is at present some controversy over the nature of the type German Schalsteins. Hentschell (1952, p. 245) states that the term has a stratigraphic connotation and should be applied only to rocks in the Upper and Middle Devonian of the Lahn–Dill region in Germany. Hence it would be best if the term were no longer used in Devonshire.

The rocks may be classified as follows:—

A. Extrusive.

1. Pyroclastic rocks:—(*a*) basic (spilitic) tuffs; (*b*) keratophyric tuffs (the Dartington tuffs).

2. Lavas:—(*a*) vesicular Spilite (the Chipley lavas); (*b*) porphyritic spilitic Andesites (Beacon Hill, Denbury Down, and Torcorn Hill lavas); (*c*) albite-augite-spilite (rare); (*d*) keratophyre (rare).

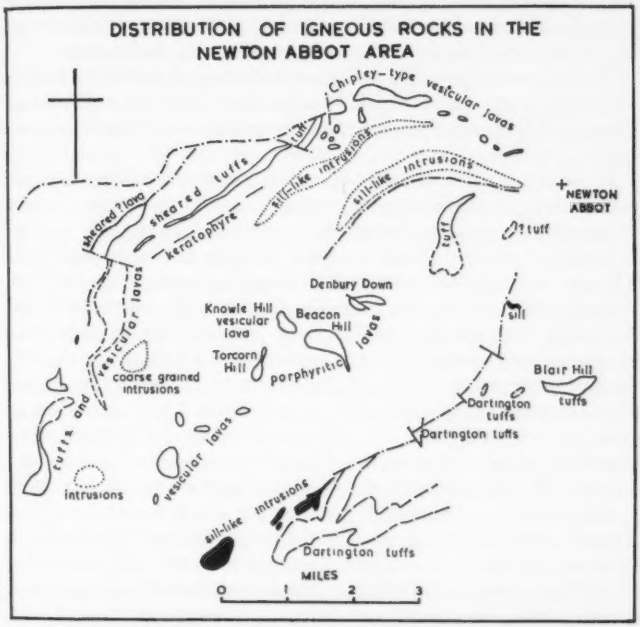
B. Intrusive.

(*a*) Spilitic dolerite; (*b*) spilitic quartz-dolerite; (*c*) picrite (rare).

Description.—1. *Pyroclastic rocks*:—Lithic and crystal tuffs are of common occurrence in the Devonian of South Devon. They have been described from the Lower Devonian of the Stoke Fleming area (Shannon and Anniss, 1931), from the Middle and Upper Devonian of Torquay (Shannon, 1924), and from the Upper Devonian (Frasnian) of Saltern Cove (Anniss, 1927). In the Newton Abbot area the chief development of tuffs is at the base of the Upper Devonian. They are commonly of keratophyric composition in the eastern part of the area (i.e., the Dartington tuffs and their equivalents), and of basic composition in the west, near Ashburton. There is also a minor development of basic tuffs associated with the lavas in the Couvinian slates below the limestone.

(*a*) *The basic tuffs.*—These are mainly found overlying the Ashburton limestone, which is of Givetian and possibly also Lower Frasnian age,

and extends from north-east of Ashburton to a few miles south of Buckfastleigh (for localities and an outline of the regional geology see Text-fig. 1). They are therefore lowermost Upper Devonian in age, and the lateral equivalents of the Keratophyric Dartington tuffs. The basic tuffs are mostly so sheared that practically nothing of their



TEXT-FIG. 2.—This sketch-map shows the distribution of igneous rocks in the Newton Abbot area. The larger intrusions are shown in solid black, and the " swarms " of small sill-like intrusions are roughly outlined by dotted lines.

original constitution can be determined, though in some cases traces of original textures survive.

In Potter's Wood (south of Buckfastleigh) the transition from limestone to tuff is exposed: a highly sheared tuff contains numerous decomposed augite crystals. The tuffs overlying the limestone at Bickington (north-east of Ashburton) contain numerous cognate lapilli, up to 2 inches in diameter, and composed of fine-grained spilitic lava.

A good example of a bomb-tuff is exposed near Austin's Bridge, Buckfastleigh. The matrix was of mud (now slate) and the bombs,

which are often several inches in diameter, are rounded and highly vesicular. In the bombs granular iron oxides are plentiful, and are normally concentrated round the vesicles, which are almost perfectly spherical in shape (indicating a sudden release of volatiles and rapid cooling). In one case there is a distinct zone of iron oxides in the slate matrix, parallel to the contact, indicating a migration of iron out of the bomb into the mud surrounding it (cf. the observations of Duschatko and Poldervaart, 1955, on the mobility of iron in spilitic rocks).

(*b*) *The keratophyric tuffs.*—These are represented by the Dartington tuffs and by the tuffs of Blair Hill and East Ogwell (south-west of Newton Abbot) which may be roughly correlated with the Dartington tuffs.

In general the Dartington tuffs are medium grained crystal lithic tuffs with a variable content of " glass " shards. A typical example shows crystals of quartz, euhedral to corroded, or broken and re-cemented by calcite. There are many cognate and accidental lapilli 1–3 mm. in length, the most typical being fragments of slate or fine-grained spilitic or andesitic lava. Feldspar crystals are common but are much decomposed: the feldspar is commonly perthite, and plagioclase may be absent. The presence of potash feldspar is extremely unusual in the volcanic rocks of South Devonshire, but was confirmed in this case by staining with sodium cobaltinitrate. The " glass " shards show characteristic shape, but are now composed of pale green, non-pleochroic chlorite showing anomalous " Berlin-blue " interference colours. The identification of this mineral as chlorite was confirmed by X-ray photographs, kindly taken by Mr. G. P. L. Walker. The refractive index was determined as $1{\cdot}610 \pm 0{\cdot}005$ and the chlorite is therefore identified as a variety near to delessite and diabantite (cf. Winchell, 1951). It is supposed that it was formed from basic glass (sideromelane), by way of palagonite, as described by Peacock and Fuller (1928) and Raw (1943). It is interesting that the birefringence of the strongly sheared chlorite is higher than that of the unsheared mineral, so that it may show low second order colours. The groundmass is composed of an irregular cement of chlorite, calcite, and chalcedony (?). The latter is also found filling holes in the shards and must therefore be a secondary mineral formed during diagenesis (cf. Raw, 1943).

The tuffs vary somewhat in texture and thickness. In the quarry in Staverton Wood (near Dartington) which yielded the goniatites referred to above, the tuff is found in two main beds, each about 10 feet thick and each bed being graded. In the railway cutting below the quarry, large angular fragments of coralline limestone (up to 15 by 6 inches in cross section) were observed in the base of one bed.

The peculiar nature of the Dartington tuffs was noted by Champer-

nowne (1889) who compared them with similar tuffs exposed south of the Newton Abbot area (at Aish, south-east of Totnes, at Waddeton, and at Clennon Hill near Goodrington). Probably these southern occurrences are of about the same age as the Dartington tuffs, which have been described here in some detail since they are important stratigraphically and since petrographically they represent a rock-type very unusual in South-West England.

The petrogenesis of such a rock presents some problems. Although quartz crystals are common, neither the cognate lapilli, nor the chlorite shards suggest an acidic parent lava. Keratophyres of potassic composition are known associated with spilites in the Devonian of Germany (cf. Lehmann, 1933). Battey (1955) has recently suggested a metasomatic origin for albite-orthoclase-cryptoperthite intergrowths in some keratophyres. The presence of potassic feldspar lapilli in a tuff however suggests that in this case the potash feldspar was originally formed as such in the magma.

In contrast with the Dartington tuffs, the Blair Hill tuffs are probably from 300–500 feet thick. They are roughly stratigraphically equivalent to the Dartington tuffs, but differ lithologically in the absence of quartz crystals. Slate fragments are also much rarer, and the whole rock is more sheared and altered in appearance. The tuffs south-west of Newton Abbot are on the same horizon and lithologically are somewhat similar to the Blair Hill tuffs.

It is thought that the Dartington tuffs and their equivalents were probably ejected from numerous small subaqueous cones. One cone is thought to have been in the vicinity of Blair Hill. The associated sediments (black slates with goniatites or a relatively monotonous benthos), suggest that possibly the water was locally fairly deep. Perhaps it is no coincidence that thick biohemal limestones are found overlying the thick Blair Hill tuffs (tuff-cone?) whereas only very thin shaly limestones are found over the thin Dartington tuffs.

That the tuffs were not all ejected from the same centre is shown by the very coarse ejecta found in some areas, and by the fact that the tuffs exposed near East and West Ogwell (south-west of Newton Abbot) may be observed to grow progressively coarser as they are traced to the north (i.e., away from the other areas of volcanic activity).

2. *Lavas.* (*a*) *Vesicular spilites* (*Chipley type*).—The excellent pillow structure of the Chipley lavas has long been admired by students and a description of both the structures and the mineralogical composition of the rock, together with an analysis, is given by Flett (in Ussher, 1913). However, due to ambiguities in the Survey Maps, the wide distribution of these lavas has not been generally recognized. They form a string of separated outcrops occurring at roughly the same stratigraphic horizon on the north side of the synclinorium which

extends west from Newton Abbot (cf. Ussher, 1913). Good pillow structure has also been observed in the lavas of Telegraph Hill, Ingsdon Hill, and in the two small masses west-south-west of South Knighton. In some of these cases a little interstitial chert or jasper is present and chert is also associated with keratophyric lavas (possibly pillow lavas) interbedded with the purple slates south of Bickington. The only other pillow lavas recognized by the author, are exposed in a small pit north of Austin's Bridge, Buckfastleigh. The pillows are much smaller than those at Chipley and interstitial chert is present. No traces of radiolaria have been found in sections cut from cherts associated with any of these examples of pillow lavas.

Sections taken at intervals across pillows fail to show the clear variolitic differentiation which has been described by Vuagnat (1946, 1949), although it does appear that the outermost borders of the pillows are rather more basic than the centre, and rather poorly developed variolitic texture has been observed in the outer part of the pillows. The amount of interstitial material between the pillows is usually negligible.

Vesicular lavas similar to the true Chipley type are also found in the southern part of the Newton Abbot area in four masses south of Woolston Green, and it is thought that these occur at about the same stratigraphic horizon. The vesicular lava of Knowle Hill may also be mentioned although it is probably of intermediate rather than basic composition, and its stratigraphic position is in doubt.

Albite is the only feldspar found in any of these rocks and augite is unknown, the only mafic minerals being chlorite, fine granular sphene, epidote, etc. For detailed petrographic descriptions the reader is referred to Flett (1913) and Shannon (1933).

(*b*) *Porphyritic spilitic andesites.*—These are the lithological equivalents of the " porphyrites " described by Fitch (1932, p. 601) from south of Buckfastleigh (in the Haredon and Marley Tunnel). They were included by Flett (op. cit.) and Shannon (op. cit.) as spilites, but although the feldspar is albite these rocks have a low colour index and are probably of intermediate composition. The best examples are seen on Torcorn Hill and on Denbury Down (Text-fig. 2). Typically the rock is not vesicular, with feldspar phenocrysts up to 1 cm. long.

The feldspar is albite, and the abundant phenocrysts are euhedral to subhedral and clear except for large chlorite inclusions. The latter are usually oriented so that they are elongate parallel to the albite twinning (010). The chlorite is light green in colour and different in appearance from that which is commonly associated with calcite in blebs or veins. Quartz may occur on the borders of some phenocrysts, or as a ramifying replacement product in the centre of the crystal. Patches of chlorite up to 1·5 mm. across occur, and in some cases the euhedral shape

indicates it is pseudomorphous after some mafic mineral, possibly augite. The groundmass consists of a fine-grained intergrowth of small albite laths, chlorite, calcite, and iron oxides.

The extrusive nature of the rocks is not fully confirmed, but the lower contact with slates (note: it is possible that due to inversion this is the original *upper* contact) shows no contact alteration of the slates. The extrusive nature is suggested by the texture, which is very fine-grained and quite unlike any of the known intrusions in the area.

A peculiar modification of the normal lava is seen on the north side of Denbury Down where a rock is found consisting of numerous rounded vesicular aggregates set in a matrix resembling the normal lava. At first sight this resembles a bomb-tuff, the " bombs " being roughly oval and about 3 inches across. In the outer part of the " bomb " the vesicles make up about 80 per cent of the rock; they are filled with calcite and have a well-rounded shape. Porphyritic feldspars are rather common, and the matrix is very fine-grained and dark with leucoxene, etc. There are some patches of fibrous yellow-green pleochroic chlorite. In the inner part, the chlorite is more abundant and is found both lining vesicles and included in calcite in the vesicles. It also replaces the feldspars. The matrix is coarser than in the outer parts of the " bombs " and small feldspar laths are clearly visible, but it is still very fine-grained. The " bombs " presumably represent centres, around which there was release of volatiles within the lava flow. The occurrence itself is at, or near the base of the Denbury Down lavas: it is possible that steam rising from the underlying wet sediments could have assisted in the formation of the vesicular " bombs ".

A rock very similar to the porphyritic spilitic andesites of Torcorn Hill and Denbury Down occurs in an old quarry on Beacon Hill (near Waterford Cross) where it shows possible pillow structure: the slates in contact with the igneous rock here show no signs of baking. This rock may be contrasted with that which makes up the main part of Beacon Hill.

The latter type is also porphyritic but the matrix is much coarser grained; furthermore purple augite is common, in thin prismatic crystals which are usually arranged in sub-parallel clusters. The augite is fresh, but the feldspars are highly sericitized. The matrix is not of the usual spilitic type but is coarser and resembles that of the finer-grained intrusions: pale green pleochroic chlorite is common in the interstices between the crystals. Iron oxides are rare.

There is considerable doubt as to whether this rock is intrusive or extrusive: but in any case it is very closely associated in space with the Beacon Hill volcanic rocks (? pillow lavas), and if intrusive, must probably be regarded as gentically connected with them.

The stratigraphic horizon of most of the spilitic andesites is in some doubt. However, it appears clear that the volcanic rocks of Beacon Hill are Couvinian in age and dip below the limestones to the east, and so the others are tentatively assigned to this horizon also. The spilitic andesites described by Fitch (1932), which are petrographically identical with those described here, may, however, be of Upper Devonian age.

(*c*) *Albite-augite-spilite*.—An unusual rock is found east of Caton Cross, near Ashburton, above the Ashburton limestone. Albite and augite phenocrysts are enclosed in a groundmass consisting of albite laths, chlorite, and aggregates of prismatic augite. The augite thus occurs in two different habits and some prismatic crystals may be observed growing out from the phenocrysts in optical continuity. Both varieties are purple in colour (? titanium rich) and it is significant that iron oxides are not present. The albite crystals carry inclusions but are not highly saussuritized and are not zoned.

There is no reason from the field evidence to doubt the extrusive nature of this rock, but if it is a lava, it is exceptional for this area in containing fresh augite. However, augite is also found in the sheared tuffs of Potter's Wood (see above) which are at approximately the same horizon (i.e., immediately above the Ashburton limestone, therefore probably Frasnian in age).

(*d*) *Keratophyre*.—Keratophyres are rare in the Upper and Middle Devonian of the Newton Abbot area. They most commonly occur as thin bands in the slates above the Ashburton limestone. The most persistent of the keratophyric horizons extends for 2 miles, although the igneous rock itself rarely exceeds 20 feet in thickness. It is probably extrusive since there are no signs of metamorphism at the contacts with the slate, and known keratophyric lavas occur both above and below this horizon. The rock is fine-grained and is largely composed of albite laths with an intersertal texture. The interstices are filled with finely granular sphene and an almost colourless nearly isotropic mineral, which may be chlorite (perhaps after glass). A pillowed occurrence of keratophyric lava at a rather *higher* horizon (interbedded with red slates) has been noted above. This rock is vesicular; and vesicular keratophyre was also found as isolated pillows at a *lower* horizon (? Frasnian), exposed in the lane half a mile south of Caton Cross.

Knowle Hill is formed by vesicular lavas of keratophyric type. There are numerous large vesicles (1–2 mm. in diameter) filled with calcite, and the groundmass is very fine-grained and consists mainly of fine feldspar laths. Just south-west of Knowle Hill a small mass of vesicular keratophyre has suffered extensive silicification. The vesicles are nearly all filled with chert; they are large and well rounded and in

some cases have coalesced to give large masses of solid chert, several inches across. The matrix is very fine-grained and there are a few rhomb and lath-shaped pseudomorphs of nearly colourless chlorite, after feldspar. The occurrence of abundant vesicles filled with chert is very unusual and proves that the chert, which is very similar to that found interstitial to some pillow lavas, is here of purely chemical (not organic) origin.

3. *Intrusive rocks.*—The minor intrusions in the Newton Abbot area are predominantly basic in character. They are almost invariably found in sills or lenticular masses. The intrusions are normally small, but the separate masses are associated together and are often concentrated in one geological horizon. They suggest a comparison with the " Laccolithic Series " of Jones and Pugh (1949), although there is no evidence that the intrusions are strictly laccolithic in form, and the tectonic setting is different. There is a resemblance in so far as the intrusions are small, sill-like in form, and associated together in " swarms " without actually coalescing to form one large intrusion.

The age of the intrusions is probably late Carboniferous, as indicated by the following facts:—

(*a*) Most of the intrusions in the Newton Abbot area occur in Upper Devonian slates: north of the area described by the author petrographically similar sills intrude Lower and Middle Culm (cf. Flett in Ussher, 1913).

(*b*) Some of the intrusions have been highly sheared by the Variscan (Asturian) earth movements.

It seems likely that the intrusions were emplaced after the beginning of the orogenic movements. This is indicated by the following facts:—

(*a*) The intrusions are usually found as sills parallel to the bedding or cleavage.

(*b*) At Torquay, the Black Head dolerite (Shannon, 1924) has been intruded into the core of an overturned fold.

(*c*) Godwin-Austen (1842, fig. 13, p. 471) figures " the ground plan of a dyke intersecting slates near West Down, between Ogwell and Ashburton " and states that " in this instance it is very evident that the intrusion of the trap was subsequent to the time the slates took their present structure ". If Godwin-Austen's observations may be relied upon then some of the intrusions must be later than others as Shannon (1922) records an instance of fossils preserving their original shape, relatively free from shearing in the hard adinoles formed round some of the intrusions.

The observations of Fitch (1932, p. 602) that " . . . the Devonian dolerites are earlier than the main earth movements, while the Carboniferous dolerites are later . . . " are believed to be incorrect, the intrusions being apparently all of approximately the same age (i.e.,

Late Carboniferous). Fitch distinguished between Devonian and Carboniferous dolerites by the presence of long needles of apatite in the former, but apatite is also common in dolerites intruded into Upper Devonian rocks and some of these intrusions (which must be of Carboniferous age) are also highly sheared.

The intrusions have received more petrographic attention than the lavas and hence only a brief addition to the earlier work will be given here (cf. Shannon, 1922, 1924; and in Ussher, 1933; Shannon and Anniss, 1933; Flett, 1913; Busz, 1896). They vary in composition from spilitic quartz dolerites (e.g., the intrusions near Dartington) to spilitic dolerites and picrite (cf. Busz, 1896). In contrast to the lavas, augite is common and is in ophitic relations with the feldspar laths. The feldspar is commonly saussuritized and sometimes it is strongly zoned (from labradorite to oligoclase or albite), in which case it is fresher than usual. In some instances zoning in the original feldspars is indicated by zoning of the inclusions in the saussuritized feldspars. In no case has an ophitic intergrowth of augite and pure unzoned albite been observed.

The augite is often fresh and occasionally shows subhedral shape. It is light lilac or purplish in colour, the colour darkening in inverse proportion to the amount of iron oxides seen in the rock (the darker varieties presumably, therefore, being iron and titanium rich). Titaniferous augites are common in rocks of the spilitic suite due to the original high content of TiO_2 in the magma (cf. Sundius, 1930). Sometimes the augite is replaced by fibrous actinolite (this is especially well displayed by the intrusions near Dartington), but more often actinolite (?) is developed only as a minute fibrous fringe to the augite, where the latter is not in contact with earlier formed minerals. Chlorite may be seen replacing augite, but the majority of the chlorite (which is often very abundant) is probably *not* formed in this way. This is proved by the following facts: (*a*) where chlorite is observed to be replacing augite it is often of a different type from that which is most common in the same slide; (*b*) augite crystals may be seen projecting into masses of chlorite, with no traces of corrosion or alteration of the augite. In these cases the augite crystal may be euhedral where it is enclosed in chlorite.

Similar phenomena have been observed by Agrell in albite dolerites from Wales (in Jones and Pugh, 1946). The ability of augite to resist alteration to low-temperature minerals has also been illustrated by Benson, who has described fresh augites in direct contact with hydrothermally-filled vesicles (*fide* Gilluly, 1935).

Recognizable pseudomorphs after olivine are absent, but it is possible that olivine was originally present in some of the more basic rocks. Hornblende is very rare; in the Newton Abbot area it occurs in

appreciable quantity in only one intrusion (west-south-west of Hele House, south-west of Newton Abbot). Primary mica is rare. Epidote is rare, but occasionally is present in large grains. It may occur in veins cutting the intrusions (e.g., in Whitecleaves Quarry, south of Buckfastleigh). Chlorite, clear albite, and calcite are common in small veins. In some cases the albite in a vein is seen growing in optical continuity with the old saussuritized feldspars of the dolerite. Apatite is common and may be abundant: the crystals may be thin and needle shaped or thick and stubby, but they are always euhedral.

A few of the intrusions contain no pyroxene. In one case it was possible to obtain specimens right across a small sill, 20 feet thick, exposed in a quarry near Lower Wickeridge (Nat. Grid. Ref. 784699). The sill is intruded into purple and green slates. The slates at the exposed upper contact are greenish-grey and under the microscope they are clearly spotted. However, the spots are far more striking in the purple slates which occur at about 2 feet from the contact. The chilled edge of the intrusion is very fine-grained, with occasional small angular fragments of metamorphosed slate which were caught up by the magma during the intrusion, and contains large porphyritic crystals of clear albite (about 0·3 mm. long). There are occasional veins of chlorite and albite. Towards the centre the texture of the rock becomes much coarser: the rock is always porphyritic but this is only clear in hand specimens from the centre of the sill. At 6 inches from the contact the phenocrysts are albite, and though fairly fresh they may be veined or replaced by calcite. At 6 feet from the contact the feldspars are saussuritized and may show zoning. At the centre the feldspars are all highly saussuritized. Thus the margin appears to be " fresher " than the centre. As the phenocrysts are present even in the micro-crystalline chilled edge they must have crystallized in the magma prior to the time of intrusion. Yet it is clear that the feldspars at the centre were originally more calcic than albite. This is therefore strong evidence that the clear albite phenocrysts in the marginal facies have resulted from the metasomatism of an originally more calcic feldspar.

There is no apatite in the marginal facies, whereas it is very abundant at the centre, proving that, in spite of its euhedral shape, apatite was not one of the first minerals to crystallize out of the magma. Chlorite is abundant, the texture at the centre being intersertal, but there is no evidence that augite was ever formed during crystallization.

Conclusion

The separation of lavas from intrusions and the establishment of a stratigraphic sequence have introduced some order into the manifestation of volcanic activity in Devonshire. However, it is emphasized that the main centres of volcanicity, south of Totnes (Ashprington),

and south of Dartmoor in the area between Plymouth and Buckfastleigh have yet to be accurately described. It is interesting to compare what little is at present known of Devonian and Carboniferous volcanicity in South-West England with the better known volcanicity of North-West Germany. In both cases volcanism began with acid tuffs in the Lower Devonian (cf. Shannon and Anniss, 1931; Pilger, 1952). The widespread extrusion of pillow lavas in the Upper Devonian (the lavas of Chipley and Pentire Head) corresponds fairly well with the " Main Greenstone " of Germany, though the former are rather later (the Main Greenstone is Upper Middle Devonian), and the basic sills may be compared with the " Deckdiabas " and " Palaeopicrit " of Nassau, which however are Lower (not Upper) Carboniferous in age.

The onset of volcanicity at rather later dates than the corresponding volcanicity in Germany is in agreement with the general tectonic setting. In the Lahn-Dill regions, the Bretonic and Sudetic phases of the Variscan orogeny were more important than the Asturian, whereas in Devonshire the Bretonic movements are not developed and the Sudetic movements seem to have been weak, whereas the main folding took place during the Asturian phase. Pilger (1952) regards the volcanic outbursts in the Nassau as having been " triggered " by minor earth movements, and if the same factor was operative in Devon the outbursts might be expected to take place rather later than in Nassau.

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Intra-Stratal Flow and Convolute Folding

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Abstract

The property of liquefaction of certain confined, water-logged, unconsolidated sedimentary layers is considered to play an important part in the development of much of convolute folding. Lateral intra-stratal laminar flow of liquefied beds, according to flow patterns mainly determined by the distribution of parts of the layers that have remained solid, appears to account satisfactorily for internal folding. Although intra-stratal flow, which can result from a number of causes, may considerably deform the stratification planes of a liquefied layer, there is neither lateral shortening nor a notable change in the thickness of the bed.

I. Introduction

It is well known in soil mechanics that, in general, gravels and sands have a good bearing value for building foundation whilst silts and clays have fair to very poor value (Terzaghi and Peck, 1948 ; Yoder, 1955). Water-saturated inorganic silts and very fine sands, rock flour, sandy or clayey silts with slight plasticity are of exceptionally poor value since they are susceptible to liquefaction and behave like viscous fluids. As indicated by De Sitter (1957, pp. 34–42), these facts are significant and their appreciation is essential to an understanding of soft sedimentary structure.

II. General Stresses and the Shearing Strength of Water-Saturated, Unconsolidated Materials

A water-saturated, unconsolidated, granular layer can be considered as being under effective and neutral stresses. The effective stress is transmitted from grain to grain in the sediment whilst the neutral stress operates in the pore-water.

Deformation of such material occurs when the resistance or shearing strength of the material is overcome. To calculate the maximum shear stress that a given material is capable of sustaining, an equation based on the empirical formula for friction of Colomb is used :—

$$s = c + (p - u) \tan \phi$$

where s = shearing strength ; c = unit cohesion ; p = unit effective stress ; u = unit neutral stress ; and ϕ = angle of internal friction.

For all practical purposes the angle of internal friction for soft saturated clays can be considered to be zero. Nevertheless all but very exceptional clays are cohesive and therefore have a shearing strength ($s = c$). They deform by plastic flow.

On the other hand saturated gravels, sands and silts may be regarded as cohesionless so that their shear strengths depend upon the effective and neutral stresses and the angle of internal friction ($s = (p - u)$

tan ϕ). The angle of internal friction is influenced by a number of factors such as shape, sorting, and particularly the packing of the grains.

Sands and gravels usually have a single grain texture, where each grain is in contact with the grains in its immediate vicinity. In addition to the single grain texture fine sands and silts often exhibit 'honeycombed' texture, where large voids bounded by many grains are developed.

When densely packed granular material is sheared and the grains slide over one another there is a volume increase. Loosely packed material on the other hand decreases in volume when subjected to shear or even vibration. If the granular material is saturated and confined, the shearing strength is either reduced or increased depending on whether the volume tends to increase or decrease, because in the case where there is a tendency to a volume decrease much of the internal support of the particles is transferred from the contacts between the individual grains to the pore-water, so that effective stress is reduced by an amount equal to the increase in neutral stress.

III. Phenomenon of Liquefaction

Quickly deposited inorganic silts and fine sands, which have little or no plasticity, have their grains very loosely packed and commonly possess a honeycombed texture. Shearing or a slight disturbance of such confined materials increases the neutral stress which may become equal to the effective stress, when the material loses its shearing strength completely and behaves as a viscous fluid. In these deposits liquefaction may even occur when the neutral pressures are increased by a change in the hydrostatic head or by a flow of water. Often a silt is so loosely packed that if liquefies on loading.

Liquefaction is not restricted to fine sands and silts for the phenomenon may be exhibited by layers of rock flour, and certain exceptional extra-sensitive clays. Thixotropic clays are occasionally encountered and in certain circumstances may lose their shearing strength and behave as liquids.

Liquefaction involves the temporary transformation of the material into a very concentrated suspension. Any movement of the liquid will obey the laws of fluid mechanics, and as soon as the flow stops the suspension will again pass into the state of a solid, and the texture of the newly-formed sediment may or may not be more dense than the original texture.

It is well known that the packing within any granular deposit varies considerably, and in sediment where loose packing prevails there may be numerous pockets of more densely packed material. In the liquefaction of silts and fine sands it is therefore to be expected that the

more dense pockets may retain a shearing strength or else they may liquefy later if there is any flow in the liquefied more loosely-packed portion.

IV. Consequences of Intra-Stratal Flow

Intra-stratal flow occurs when there is movement in the horizons which are subject to liquefaction in a sequence of water-saturated, unconsolidated deposits. If flow has taken place in a liquefied layer, evidence is to be expected in the consolidated equivalent. Much of what has been variously termed ' curly bedding ', ' hassock bedding ', ' slip bedding ', ' internal crumpling ', ' convolute bedding ', ' convolute folding ', etc. is considered to be this evidence.

Convolute folding occurs within a layer which is usually not itself folded. These internal folds are complete and die out towards the smooth upper and lower margins of the bed, and though the contorted laminations may vary in thickness they are continuous.

Many have considered the convolute folds within a layer to have formed after the deposition of overlying beds, and have recognised that these internal contortions are associated with movement within certain water-logged layers. Brown (1938, p. 360) suggested that small-scale contortions and lenses within layers of the Tertiary rocks of the Santa Elena peninsula, Ecuador, resulted from ' flow like a very viscous fluid ' when those layers had been confined, unconsolidated and water-saturated, and had acted as the slip planes described by Baldry (1938). Associated with these internally deformed layers are sandstone dykes which penetrate adjacent beds (Baldry, 1938, p. 352 ; Brown, 1938, pp. 366–367). Rich (1950, p. 729) considered the contortions within the Aberystwyth siltstone layers in Wales to have formed in confined layers because the laminations in the convolute folding thin but do not break as the top of a bed is approached, and proposed that they originated whilst " the siltstone was still unconsolidated, and perhaps so filled with water that it was essentially in a condition of quicksand ". Rich goes on to suggest that the quicksand layer " served as a zone of gliding along which the entire mass of overlying sediment crept down a slope and, in the process, crumpled the bedding within the siltstone, in which the movement was concentrated ". Williams (1959, p. 31) noted that current bedded tops of fine grained sandstone layers of the Upper Scamander sequence in Tasmania were involved in convolute folding, and concluded that the deformations were post-depositional structures, and that there had been a tectonic control over their formation. Yet another cause has been given for convolute folding recorded in a layer of interbedded sandstone and siltstone which dips at less than 1° at Awa-awa beach, New Zealand, for the layer is considered to have retained water and moved under the pressure of the overlying beds (Ongley and Macpherson, 1941).

Despite the early recognition that convolute folding was formed by movement within confined, unconsolidated, water-logged layers, these internal deformations have remained problematical because no satisfactory movement pattern has been suggested for their formation.

V. Mechanism of Convolute Folding

Doubtless distortion of soft sedimentary layers may result from many phenomena, but flow within liquefied layers is considered to play an extremely important part especially in the development of convolute folding.

In general, intra-stratal flow within liquefied layers appears to result from a number of causes amongst which are shear stress due to downslope sliding of sediments either under the influence of gravity or through tectonic folding, transference of a small volume of material of the liquefied bed laterally into crests and troughs during folding of the layers, and transference of material in the form of an intrusion into adjacent beds. Such flow obeys the laws of fluid flow and must cause an internal deformation of the viscous fluid layers throughout a considerable lateral extent.

In laminar flow (Eshbach, 1952), where one fluid lamina slides over another lamina in such a manner that all turbulent fluctuations are damped out, any elemental volume of the liquid undergoing deformation remains approximately constant. Laminar flow does not necessarily require the flow laminae to be planar and they may bend through quite acute angles. Since there is no flow across flow laminae the width of any " marker horizon " being deformed by laminar flow remains constant in the direction of flow if the flow laminae are parallel. If however the flow laminae diverge or converge the thickness of a " marker horizon " is reduced or increased (Text-fig. 1). Carey (1954, p. 92) describes the geometry of deformation of a rheid according to laminar flow.

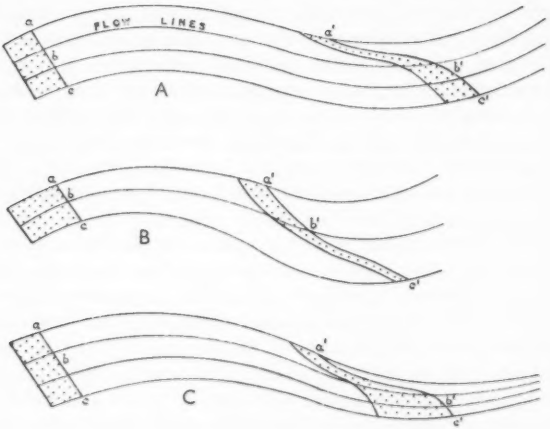
If laminar flow resulted from movement within a liquefied layer it would form a pattern, which would be determined mainly by the distribution of the material that had retained a shearing strength and had remained solid, such as the coarser-grained material, the cohesive sediment and the pockets of more densely packed sediment.

Text-figures 2B and 2C illustrate diagrammatically the deformation that would be noted in a section of a stratified sedimentary bed which had liquefied, and in which laminar flow had occurred during the transference of a small amount of material across the face of the section from left to right, and in planes in the general direction of bedding, according to the flow pattern of text-figure 2A. Similar deformation due to laminar flow may be noted in a section of a stratified layer which had liquefied and was submitted to a shear stress resulting

from buckling or the gravitational downslope movement of water-logged sediments. With such intra-stratal flow the attitudes of the axial planes of resulting internal folds may be irregular, and their direction of recumbency inconsistent.

It is conceivable that leaves of solid material may become broken during flow within a liquefied layer, so that when the suspension passes into a solid state it would have a brecciated appearance.

The pockets of material that retain a shearing strength in a liquefied layer may disappear during flow altering the flow pattern, and more



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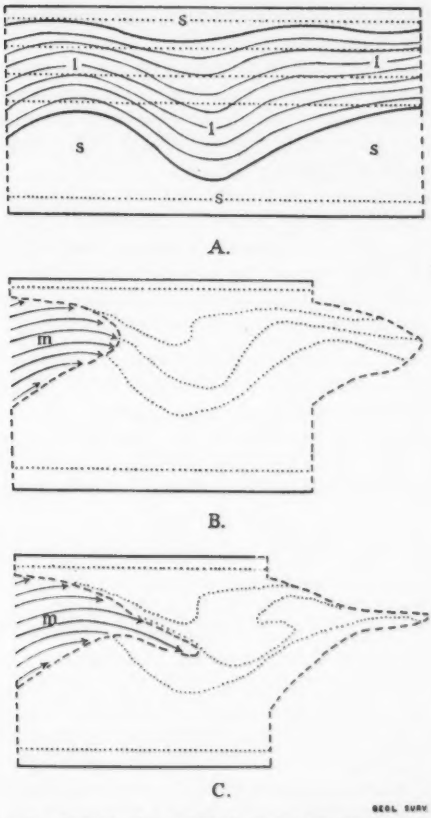
TEXT-FIG. 1.—Diagrammatic sections perpendicular to a " marker horizon " (dotted) deformed by laminar flow from a position abc to a'b'c'. Areas of horizon delimited by flow lines remain constant. Thickness of horizon in direction of flow remains constant when deformation is along parallel flow lines (A), but decreases with divergent flow lines (B), and increases with convergent flow lines (C).

complicated distortions within the stratified layer would result. Complicated folding may also be formed by repeated flows within a layer, or by turbulent flow due to high velocities of flow which may be expected in liquefied horizons that have acted as gliding surfaces.

VI. Concluding Remarks

It appears likely that difficulty has been experienced in envisaging convolute folding within stratified layers as being due to lateral movement because it is evident that the contortions are not formed by lateral shortening, and explanations of the folds have been attempted



TEXT-FIG. 2.—A. Section of a confined, water-saturated, sedimentary layer at right angles to stratification (stippled lines). A laminar flow pattern is indicated by continuous lines in the general direction of bedding within a portion of the layer that has liquefied (l). Flow pattern is mainly determined by the distribution of parts of the layer that have remained solid (*s*).

B and C. Diagrammatic sections of internal folds resulting from transference of material (*m*) in the direction and distance indicated by the arrows, according to the flow pattern of A.

in terms of vertical adjustments (Kuenen, 1953 ; Ten Haaf, 1956) or irregular distributions of pressure or suction (Holland, 1959) during the deposition of the layers that are internally deformed. Although there may be examples where convolute folds have formed during deposition these are considered exceptional, for sound arguments have

been given in favour of their formation after the deposition of the overlying beds (Rich, 1950, and others).

If convolute folds result from laminar flow in the general direction of bedding within a liquefied layer there is neither lateral shortening of the stratification planes nor a notable change in the thickness of the bed, except in cases where the flow results from a thickening and thinning of the layer during its folding.

In conclusion it may be pointed out that whatever the cause of liquefaction and movement within a susceptible layer, in cases of simple intra-stratal flow it is possible to deduce only that flow occurred perpendicular to the axes of the convolute folds, for owing to the irregular attitudes of the axial planes and directions of recumbency, the actual direction of movement cannot be determined.

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Petrography of the Mesozoic Succession of South Wales

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Abstract

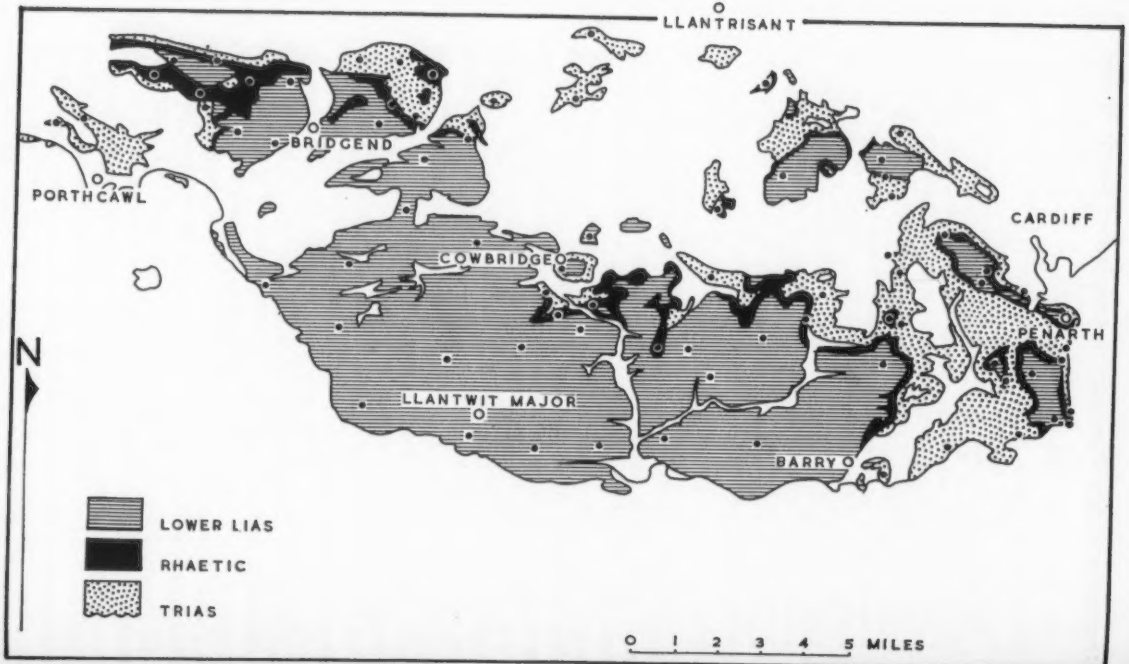
The heavy mineral suites of the Trias, Rhaetic and lowermost zones of the Lower Lias in the Vale of Glamorgan of South Wales are described. The northerly coastline of the Mesozoic sea, roughly coincident with the present-day periphery of the Coalfield, consisted mainly of Carboniferous Limestone and in places, the Old Red Sandstone and Millstone Grit. The mineral assemblage at any particular point in the littoral zone was determined largely by the nature of the outcropping rocks of the coastal mainland, the derivation of detritus being very localized. Within this zone some degree of gravity sorting of the detritals occurred, this implying a relatively steeply inclined coastal sea-bed. An off-shore current carried detritus from the Armorican land-mass of Britanny and granite of South-West England to this area where the detritals were dispersed thinly throughout the locally derived sediment.

Introduction

Mesozoic strata outcrop in the Vale of Glamorgan against the southern margin of the South Wales Coalfield and are comprized of the Trias, Rhaetic and part of the Lower Lias. The distribution of these rocks is shown in the sketch-map (Text-fig. 1). These strata follow one another conformably except for a sharp plane of erosion between the Rhaetic and Trias. The Trias has been investigated, amongst other authors, by Miskin (1919), the Rhaetic by Richardson (1905), and the Lias by Woodward (1888) and Trueman (1920, 1922 and 1930). These authors were concerned chiefly with the stratigraphy and palaeontology of the strata whilst the study now described concerns an interpretation of the heavy mineral suites of this Mesozoic succession.

Pringle and George (1948) have reviewed the geology of this area. "The earlier sediments were laid down on an irregular subsiding floor of a great salt-lake basin, . . . and the overlap and overstep of the beds provide a clear picture of the progressive submergence of the land. As each of the formations approaches the old shore-line the normal facies is replaced by one of littoral type, so that the margins of the basin and the sites of ridges which rose as islands may be clearly recognized. . . . As a result of continued depression, however, it is likely that the whole of the region was submerged before the close of the Mesozoic era . . . ".

Off the mainland, which lay to the north and north-west, there were islands generally composed of Carboniferous Limestone. Near the shore-line and around such islands the littoral deposits accumulated. Within the Trias the marls, deposited at some distance from the shore, tend to give way to breccias, conglomerates and limestones near the shore-line. The Rhaetic shales tend to give way to interbedded sandstones, oolitic limestones and shales, whilst the Lower Lias limestones



TEXT-FIG. 1.—Geological sketch-map showing distribution of the Mesozoic rocks of the Vale of Glamorgan and approximate location of the collecting points of some specimens (based on 1-in. maps, published by H.M. Geological Survey).

and shales tend to give way to limestone conglomerates in the littoral zone.

Experimental Procedure

Over 100 specimens were collected from the Triassic, Rhaetic and Liassic strata, and the sketch-map (Text-fig. 1) indicates approximately the position of many of the collecting points. The samples of sandstone, shale and marl were crushed, and a sandy residue obtained from the limestone specimens by treatment with cold concentrated hydrochloric acid. All samples were then dispersed in a weak solution of sodium hexametaphosphate, and particles of 0·02 mm. diameter and below removed by repeated decantation after sedimentation. The coarser material (0·2 mm. diameter and above) was separated by sifting with a 70 I.M.M. sieve. The residue corresponds to fine sand and optical study was concentrated chiefly upon this grade since it contained the bulk of the heavy minerals. These were separated in bromoform, identified, and their relative proportions determined by microscopic counts of up to 300 grains in each sample. Unfractionated samples from each specimen were also examined in order to study the light minerals and to pick up any heavies that might have been trapped in the light fraction.

The iron oxides and dolomite are very abundant and widespread, occurring in all samples examined. Chlorite is likewise widespread and locally abundant. Barite, selenite and aragonite are not widespread but locally can be very abundant. Hence these mineral species have not been included within the grain counts as they would obscure the remaining data.

Description of the Heavy Mineral Species Identified

During the course of the work the following minerals have been found:

Cubic:—fluorite, galena, garnet, magnetite, pyrite.

Tetragonal:—anatase, rutile, zircon.

Hexagonal-trigonal:—apatite, calcite, dolomite, haematite, ilmenite, quartz, tourmaline.

Orthorhombic:—aragonite, barite, brookite, dumortierite, hypersthene, staurolite, topaz, zoisite.

Monoclinic:—biotite, chlorite, clinozoisite, pistacite, hornblende, monazite, muscovite, selenite, sphene.

Triclinic:—kyanite.

Non-crystalline:—leucoxene, limonite-goethite.

The occurrence of the heavy minerals and their relative proportions in the various stratigraphical divisions and lithological types are shown in Table 1.

Iron oxides:—Limonite is the most abundant and widespread opaque

heavy mineral. It is apparently present in considerable quantities in all strata, although a cautionary note has to be introduced. Within the Triassic sandstones of the Bristol region investigated by Ollier (1954), goethite, identified by X-ray diffraction analysis, is the most abundant iron oxide, but the external appearance of the grains is frequently affected by a coating of limonite.

Haematite is quite widespread, and in coastal sediments dominated by detritus from islands of Carboniferous Limestone it is virtually the sole opaque heavy mineral present in the mineral assemblage.

Ilmenite is neither abundant nor widespread. It rarely dominates the heavy mineral assemblage as it does within the specimen of Liassic limestone collected near Dunravon Castle approximately four miles south-south-west of Bridgend (grid reference—28841732). The surface of an ilmenite grain is often altered to leucoxene completely or in patches.

Magnetite octahedra, and *pyrite* and *galena* cubes are of rare occurrence, the latter only within the Liassic limestones.

Carbonates :—Calcite and *dolomite* are not confined to the limestones but occur in all samples examined and serve, within the Triassic and to a lesser extent the Rhaetic sandstones, as cementing media. Within the crushed, separated sample the calcite generally occurs as irregularly broken plates and the dolomite as rhombs. The variable friability of the sandstones is a reflection of the differing amounts of cementing material present. The white Rhaetic sandstones are relatively friable and the cementing material at a minimum. Most Triassic sandstones, usually red and seldom grey, are much harder and well cemented with calcite and particularly dolomite, which may be present as very large rhombs. The amount of cementing material present may be considerable and the quartz grains not in contact, indicating, as Ollier (1954) notes, that chemical deposition of the calcium carbonate took place concurrently with deposition of the sand grains.

There is a complete transition from carbonate cemented sandstones, through sandy limestones, to very pure limestones. Although for convenience, whilst comparing the data of the heavy mineral assemblages shown in Table 1, specimens have been described as sandstone or limestone, in some cases this division is somewhat arbitary. With increase of the silt and clay fraction there is a similar transition from the red Triassic sandstones to red marls. Albeit, as outlined in the introduction, the marls dominate the lithology of the Trias in the east of the Vale of Glamorgan and are particularly well displayed in the cliffs south of Penarth, whilst the calcareous sandstones, sandy limestones and pure limestones become more important in the west of the Vale where they are interbedded with marls and the limestone conglomerates, and represent the littoral facies of the Trias. Altogether the lithology and

TABLE 1.

Relative (%) proportions of heavy mineral species in grain counts. * indicates less than 1%	LOWER LIAS				RHAETIC										TRIAS					
	Limestone	Shale		Sandstone					Limestone				Shale		Sandstone	Limestone				Marl
	Combined counts	Sample 1	Combined counts	Sample 2	Combined counts	Sample 3	Sample 4	Sample 5	Combined counts	Sample 6	Sample 7	Sample 8	Combined counts	Sample 9	Combined counts	Sample 10	Combined counts	Sample 11	Sample 12	Combined counts	Sample 13
Zircon	49	50	54	49	30	23	28	58	51	61	27	50	51	48	62	71	60	57	32	73	81
Garnet	9	8	10	14	28	41	0	0	24	15	61	0	20	19	14	13	12	14	54	1	0
Tourmaline	17	16	10	10	20	14	31	35	10	11	4	15	8	10	9	5	11	9	8	5	2
Rutile	12	10	17	17	12	12	18	7	11	9	6	11	12	14	10	8	9	7	6	13	9
Epidote	3	4	2	5	*	1	0	0	2	2	1	4	4	6	1	1	2	4	0	1	1
Anatase	2	3	2	2	2	0	7	0	*	0	0	0	2	0	*	0	2	3	0	*	1
Apatite	2	2	0	0	5	6	0	0	*	0	0	6	1	1	1	0	*	0	0	5	3
Monazite	3	5	4	2	0	0	0	0	1	2	0	0	1	1	1	1	1	2	0	*	1
Fluorite	1	0	0	0	0	0	0	0	*	0	0	7	0	0	0	0	*	1	0	*	0
Brookite	1	1	0	0	2	0	11	0	0	0	0	0	*	0	*	0	*	1	0	0	0
Staurolite	1	1	1	0	1	2	0	0	*	0	0	0	0	0	1	1	1	0	0	1	0
Hypersthene	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	*	2	0	0	0
Hornblende	0	0	0	0	0	0	0	0	0	0	0	0	*	0	0	0	0	0	0	0	0
Kyanite	0	0	0	0	0	0	0	0	0	0	0	0	*	1	0	0	*	0	0	0	0
Sphene	0	0	0	0	*	0	3	0	0	0	0	0	0	0	0	0	*	0	0	*	1
Topaz	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Dumortierite	0	0	0	0	*	1	0	0	*	0	0	7	*	0	0	0	*	1	0	0	0

the status of the carbonates within the Triassic rocks is very similar to that described by Ollier (1954) and Thomas (1940) who describes the Triassic rocks of North-West Somerset.

This investigation has not been extended to the limestone conglomerates within the Trias and Lias since it would then become, essentially, a study of the Carboniferous Limestone which has already been undertaken (Crampton, 1960). In the Lias the conglomerates have been termed the Southerndown or Sutton Stone type of lithology and they usually rest directly against the surface of the Carboniferous Limestone as often occurs, but by no means always, in the Trias.

Aragonite is not widespread in the Trias but can be locally abundant. For example it constitutes, together with calcite and dolomite, the cementing medium of a specimen of sandy marl collected near Wenvoe approximately three miles north of Barry (grid reference—31281738). It occurs in the sample as colourless, irregularly broken plates showing twinkling and very strong birefringence. The most useful feature was the often located, biaxial, negative interference figure showing a very low optic axial angle of about 20°.

Sulphates :—Barite is widespread throughout the Mesozoic rocks examined, but never abundant. It can occur as angular fragments determined by fracture and cleavage, or as small irregular fragments, the shape being determined by the interstices which they originally filled before the crushing of the specimen. The fragments usually display a yellow-brown staining and contain many minute inclusions. In addition to its high refractive index and moderate birefringence, occasionally the positive biaxial interference figure was located.

Selenite is not widespread in the Trias and is abundant only very locally. Veins of this mineral can be seen in the cliffs south of Penarth. When located, it usually occurs as pseudo-rhombohedral cleavage fragments showing a low refractive index. Haematite, the carbonates and sulphates are all of authigenic origin.

Chlorite is common in all the strata investigated, and is sometimes abundant. Typically, it occurs as colourless to green plates, sometimes slightly pleochroic, and showing ultra-blue polarization tints. A few grains may display granular extinction, may be fibrous, and may show considerable indentation of the margin, even in samples not treated with concentrated hydrochloric acid.

Zircon is the most abundant and widespread non-opaque constituent of the assemblage for which grain counts are available. It is generally colourless, but a few purple, pink, red and brown grains have been located. Pleochroic brown zircon tends to be more common in the Trias. The grains are usually clear, but some have become clouded with inclusions and a very few are nearly opaque. The zoning of colour and inclusions infrequently occurs. From a sample of the Triassic

limestone collected near Llanharry, approximately six miles east of Bridgend (grid reference—30031801), a large proportion of the zircons have been heavily stained red-brown, a colour that remained after treatment with concentrated hydrochloric acid. Rich haematitic ore is mined from the Carboniferous Limestone in this area and Pringle and George (1948) suggest the local replacement of the top of the Carboniferous Limestone by haematite iron ores from percolating Triassic waters.

Most zircon grains show pronounced rounding and in some cases, fracturing. A less frequent but persistent form of zircon is the markedly euhedral crystal showing only slight rounding of the crystal edges, an appearance of rounding in a few cases being due to excessive faceting at the terminations. This form has been described, in particular, in the suite of the Millstone Grit (Crampton, 1960).

Garnet shows a pronounced uniformity in all the Mesozoic strata investigated. The grains are colourless or tinged with pink and usually display a strong hackly outline. Less common are the more rounded or splintery fragments. Inclusions are often quite numerous. Only a few grains show anomalous incomplete extinction, most being isotropic. A rich local source of garnets of this character is the Old Red Sandstone (Heard and Davies, 1924).

Tourmaline generally occurs as rounded flakes which are often pleochroic in roughly equal proportions of green and brown within the Lias, with brown tourmaline showing a slight preponderance in the Rhaetic and green tourmaline in the Trias. Pink, mauve, blue and yellow or parti-coloured grains are much less common. Some opaque inclusions are often present. Near-euhedral prisms with rhombohedral terminations showing only slight evidence of abrasion are widespread but less common.

Rutile usually occurs as well-worn, oval-shaped grains. Most are yellow, except in the Rhaetic where red and yellow rutile occurs in approximately equal proportions. Near-euhedral rutile, showing only slight rounding, tends to be yellow in colour and shows striations parallel to the principal axis of the crystal or oblique to the prism edge due to polysynthetic twinning. Table 2 shows the generally even distribution of this mineral throughout the Mesozoic rocks.

The following mineral species are present in much smaller amounts compared with the four most common species, zircon, garnet, tourmaline and rutile. The *epidote group* includes pistacite and both zoisite and clinozoisite. Yellow *anatase* and colourless rounded plates of *apatite* are quite widespread. *Monazite* grains are usually well-rounded, yellowish, with their margins clouded with alteration products. Pleochroic yellow *staurolite* grains displaying a hackly fracture; isotropic, colourless, authigenic *fluorite* crystals, and yellow *brookite*

showing incomplete extinction are successively less common. Irregular but somewhat rounded *dumortierite* prisms, showing a patchy colouring of blue, brown and green, display maximum absorption when the {100}-cleavage lies parallel to the vibration direction of the polariser. Ragged, green basal flakes of *hornblende* ; pleochroic green to pink prisms of *hypersthene*; colourless and elongated *kyanite* crystals showing some cleavage traces; wedges of *sphene*, and irregular, glassy grains of *topaz* showing a delicate blueish tinge, are rare.

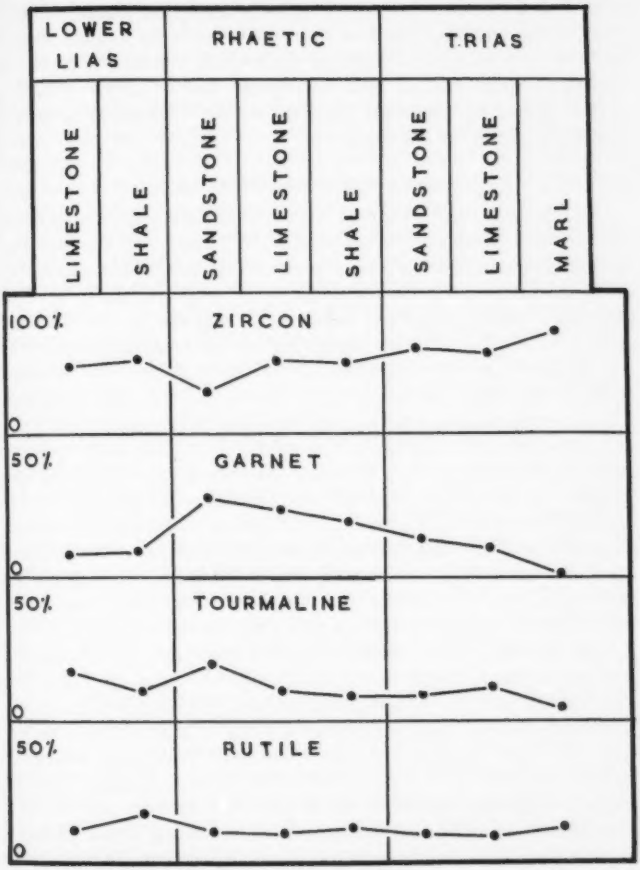
Distribution and Interpretation

(*a*) *Sorting in the Littoral Zone*

Text-fig. 2 shows the distribution of the four most common heavy mineral species throughout the various Lower Lias, Rhaetic and Triassic lithological types. An interesting feature of this distribution is the increase in rutile content in the argillaceous deposits of these strata (least pronounced in the Rhaetic) over that of the sandstones and limestones. The relative proportion of zircon shows a similar increase from the shallow-water sandstones to the deeper-water shales or marls. In particular there is a striking rise in the zircon content within the heavy mineral suite of the Trias, showing a maximum, in the marls where the proportion can rise to 81 per cent (sample 13, Table 1, collected near Ruthin, approximately three and a half miles east-north-east of Bridgend; grid reference—29701802) or higher. In contrast the zircon content of the Rhaetic sandstones of the littoral zone drops to 30 per cent, and garnet and tourmaline can be of equal quantitative importance within the assemblage.

Text-fig. 2 reveals the contrasting relationships regarding garnet and tourmaline. An extremely small amount of garnet was deposited in the deeper Triassic waters represented by the marls. Nearer the shoreline considerably greater quantities of garnet were present in the accumulating sediment. Garnet is more plentiful throughout the Rhaetic deposits, but there is a similar increase in relative proportion from the deeper-water sediments to the sandstones of the littoral zone where garnet was more abundant than at any other time in the Mesozoic of this area. There is a sharp drop in the quantity of garnet deposited in the Liassic sediments. Possibly much of the outcropping Old Red Sandstone, a rich local source of these garnets, was submerged by Liassic times in the steadily extending Mesozoic sea. The slightly higher garnet content of the shales is at variance with the previous results. Within the Trias, Rhaetic and Lias there is a noticeable increase in the tourmaline content from the shales to the limestones and sandstones.

Thus garnet and tourmaline bear a reciprocal relationship with



TEXT-FIG. 2.—Graphical representation of the relative proportions (%) of the four most common heavy mineral species within the combined grain counts for the various Lower Lias, Rhaetic and Triassic lithological types.

zircon and rutile; the former increase in quantitative importance towards the shore-line whilst the latter decrease. The increase of garnet and tourmaline towards the mainland could be taken as an effect of the source of material being in that direction, but the opposite relationship of the zircon and rutile is somewhat difficult to explain on this basis. However, assuming a local source for much of the material

contributed to these sediments, it would appear that garnet and tourmaline, the lighter of the four most common heavy mineral species, tend to be retained in the littoral zone, whilst zircon and rutile, the heavier mineral species, tend to migrate out to deeper waters, a certain degree of large-scale " gravity sorting " occurring within the coastal waters of the Mesozoic sea.

(*b*) *Local content of Detritus*

As Trueman (1922) remarks, the content of the conglomerates of the littoral zone, particularly those within the Triassic and Liassic rocks, in which there is a remarkable scarcity of argillaceous and arenaceous material from the inner mainland where extensive areas of Coal Measures were undergoing denudation, suggests a very localized source of material with few large rivers contributing large quantities of sediment from the hinterland to the littoral zone. The combined grain counts shown in Table 1 can be deceptive to the extent that there may be marked variations in the relative proportions of the more common heavy minerals present in the sediments from point to point. Locally garnet can be very abundant, as for example within the very limited mineral assemblage of the Triassic limestone sample 12, collected just south of Llanharan (grid reference—30061828). Isolated outcrops of the Old Red Sandstone probably occurred on the mainland near the shore-line, distributing garnet generally throughout the Mesozoic sea and particularly in the littoral zone, and also giving rise to concentrations in the immediate vicinity of the outcrops.

The Rhaetic shallow-water sediments offer particularly striking evidence of the localized derivation of material. As in the Trias there are marked variations in the garnet content. The sandstone sample 3, collected one and a quarter miles south of Cowbridge (grid reference—29961727), and limestone sample 7, collected three miles south-east of Cowbridge (grid reference—30321713) contain unusually abundant garnet, suggesting proximity to a shore-line outcrop of Old Red Sandstone. The Old Red Sandstone hill of Stalling Down probably represents an uncovered relic of this shore-line outcrop. In or near the littoral zone but outside the immediate vicinity of outcropping Old Red Sandstone there should be a corresponding sharp decrease in the garnet content. The assemblage of the sandstone sample 5, collected three miles north-east of Bridgend, (grid reference—29511817) contains no garnet whatsoever.

A further sample of Rhaetic sandstone collected at St. Mary Hill approximately four miles east-south-east of Bridgend (grid reference—29661787) contained abundant angular flakes of haematite and numerous broken quartz euhedra in addition to much dolomite in an otherwise limited suite of zircon, tourmaline, rutile and anatase. This

assemblage, particularly the haematite and quartz euhedra, is characteristic of the Carboniferous Limestone (Crampton, 1960). The presence of quartz euhedra which although broken still retain very sharp edges, indicates a very localized source of material. The Carboniferous Limestone at St. Mary Hill undoubtedly formed an island ridge within the Rhaetic sea and contributed nearly all the material within this specimen. Quartz euhedra were frequently located in the Rhaetic sandstones suggesting that the Carboniferous Limestone constituted an important part of the mainland and near-by islands.

A final example is afforded by sample 4, collected two miles north-west of Bridgend (grid reference—28771816). Table 1 illustrates the unusually rich titanium suite of rutile, brookite, anatase and sphene. Both Simpson (1932) and Griffiths (1939) refer to work by Stuart and Pascoe concerning a similarly rich suite in the Basal Grit of the Millstone Grit. These rocks outcrop to the north of the Rhaetic sandstone in question and probably formed part of the shore-line of the Rhaetic sea from which this suite was derived.

These examples illustrate the pronounced local derivation of material, particularly along the Rhaetic shore-line. This coast-line, roughly coincident with the present-day escarpment enscribing the South Wales Coalfield, was characterized by considerable outcrops of Carboniferous Limestone, and also Old Red Sandstone and Millstone Grit similar to those of the present-day. As Trueman (1922) suggests, the present landscape of South Wales is essentially that of the pre-Liassic period being re-exposed by the removal of the softer Mesozoic cover. There was no pronounced deltaic development along the Mesozoic coastline.

The mainland outcrops described above were capable of supplying many of the heavy mineral species located within the Mesozoic sediments. Predominantly rounded grains of zircon, tourmaline and rutile could have been derived from the Old Red Sandstone (Heard and Davies, 1924), Carboniferous Limestone and Millstone Grit (Crampton, 1960), or Coal Measure sandstones (Heard, 1922) if these contributed any significant amount of material. Near-euhedral zircon could have been derived, in particular, from the Millstone Grit, and the garnets chiefly from the Old Red Sandstone. Although locally the Millstone Grit suite has contributed material to the Rhaetic littoral deposits, the very small amounts of red garnet in the Mesozoic sediments suggests that the outcrop of this Grit along the coastline was very limited.

(*c*) *Far-travelled content of Detritus*

There remain the few minerals, staurolite, kyanite, topaz, hornblende, hypersthene and dumorierite, which are present in the Mesozoic strata in very small amounts. These could not have been derived from

local strata and a distant northerly source is unlikely because of the dominantly local character of the coastal sedimentation described above. To the south there are the granitic masses of South-West England and the metamorphic rocks of Brittany.

Brammall (1928) has described the heavy minerals within the Dartmoor granite and the detritals dispersed from this granite at the present day. He adds, " The nature and distribution of the exposed granites indicate that similar types were among the earliest granites to be exposed on the Moor. Hence the mineral associations characterizing the detritals of today may have been characteristic of detritus dispersed from the granite during a long geological period dating back from the present to some remote post-Carboniferous epoch still to be determined ". Many of the more common heavy minerals within the Mesozoic strata of South Wales could have been derived from this granite mass, but it is more probable that they were derived locally from the sediments outcropping along the Mesozoic shore-line. Topaz within the Triassic marls, and hornblende, located in the Rhaetic shales, could have an origin within the granites. The strongest evidence of detritus being carried north from the granite, is however, the presence of dumortierite which is uncommon but widely distributed throughout the Rhaetic littoral and deeper-water deposits, and is present in unusual amounts in the limestone sample 8, collected just south of Penarth (grid reference—31871707). Dumortierite has also been located within the Triassic limestones, but not in the Lias.

This mineral is associated with andalusite, green spinel and sillimanite and greater amounts of cordierite, the assemblage being widely distributed among the normal granites but particularly in marginal and high level types carrying xenoliths of cordierite-bearing hornfelsed shale. Brammall notes their generally rare occurrence in present day detritus but adds that this " . . . must differ markedly from the detritals dispersed from the area while early denudation was effecting the removal of the country rocks roofing the granite. These rocks doubtless included an extensive development of altered sedimentaries comparable to xenoliths of hornfels in the granite and to contact-altered rocks now exposed around the granite margins ". That cordierite, the most abundant mineral in this particular assemblage, has not been located in the Mesozoic sediments of South Wales is probably due to the unlikelihood of cordierite surviving the conditions prevailing in detrital accumulations before their consolidation.

The minerals kyanite and staurolite in particular are, if a northerly source is excluded, probably derived from the old Armorican land-mass, with Brittany as a present-day remnant. This source of stress minerals has been suggested for the diachronic sands of Upper Lias and Lower Inferior Oolite age in the West of England by Boswell (1924), and for

the Bunter Pebble Beds of the South-West of England by Thomas (1902). Thomas concluded that the heavy mineral species and their distribution in the finer material of the Pebble Beds indicated that a current bearing sediment from the Armorican massif to the south was joined about twenty miles north of the coast by a westerly minor current bearing material from the high land of Devon and Cornwall to the west. It would seem that the heavy mineral species in the Mesozoic rocks of the Vale of Glamorgan indicate a continuation of this current northwards from South-West England to the South Wales area, bringing detritus from both the Armorican massif and granitic highlands of South-West England. This current, having distributed material along the coastal deposits of the Bunter Pebble Beds during Triassic times, also caused a drift of pebbles along the Lower Liassic shore-line of South Wales according to Trueman (1922). Boswell (1924) also concludes that a current-drift northwards along the coast carried material from the two sources described as far as Wiltshire and Gloucestershire during Upper Lias and Lower Inferior Oolite times.

Conclusions

Apart from one short break the Trias, Rhaetic and that part of the Lower Lias represented in South Wales were laid down, outside the littoral zone, as a continuous sedimentary succession within a steadily extending Mesozoic sea, bordered by land to the north approximately coincident with the present-day periphery of the Coalfield, and to the north-west. The geology of the old land surface at present being re-exposed by denudation of the Mesozoic cover, and the coastal conglomerates of the Trias and Lower Lias, indicate that the coastal mainland and near-by islands consisted mainly of Carboniferous Limestone. The heavy mineral suites of these Mesozoic strata suggest that the sea was also bordered in places by the Old Red Sandstone and, to a lesser extent, the Millstone Grit.

The derivation of material deposited within this sea was very local, little detritus being carried from inland regions by large rivers. Thus the mineral assemblage at any particular point in the littoral zone was determined largely by the nature of the outcropping rocks of the coastal mainland. This is particularly evident within the Rhaetic sandstones. It is suggested that much of the Old Red Sandstone was submerged by Lower Lias times, leaving predominantly Carboniferous Limestone outcropping along the coast. Within the littoral zone some degree of gravity sorting of the detritals occurred, the lighter minerals such as garnet and tourmaline tending to be retained in the littoral zone whilst the heavier minerals such as zircon and rutile tended to migrate out to deeper waters, possibly under the influence of a drift along-shore. This process implies a relatively steeply inclined coastal sea-bed.

An off-shore current carried detritus from the Armorican land-mass of Brittany and granite of South-West England to this area where the detritals were dispersed thinly throughout the locally derived sediment. This current is probably synonymous with that responsible for the deposition of the Bunter Pebble Beds of South-West England and the diachronic sands within the Upper Lias and Lower Inferior Oolite of the West of England.

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Ignimbrite in the Kilchrist Vent, Skye

By P. S. Ray

(PLATE VII)

Abstract

Ignimbrite steeply intrusive into the basaltic agglomerate of the Kilchrist vent is described. Like the intrusive ignimbrite near Kilchoan, Ardnamurchan, it shows flow structure parallel to the walls, flow being similarly expressed by the elongation and alignment of the constituent shreds of devitrified glass and pumice lapilli. Fragments of basalt, derived from the vent agglomerate, are sometimes also drawn out in the direction of flow.

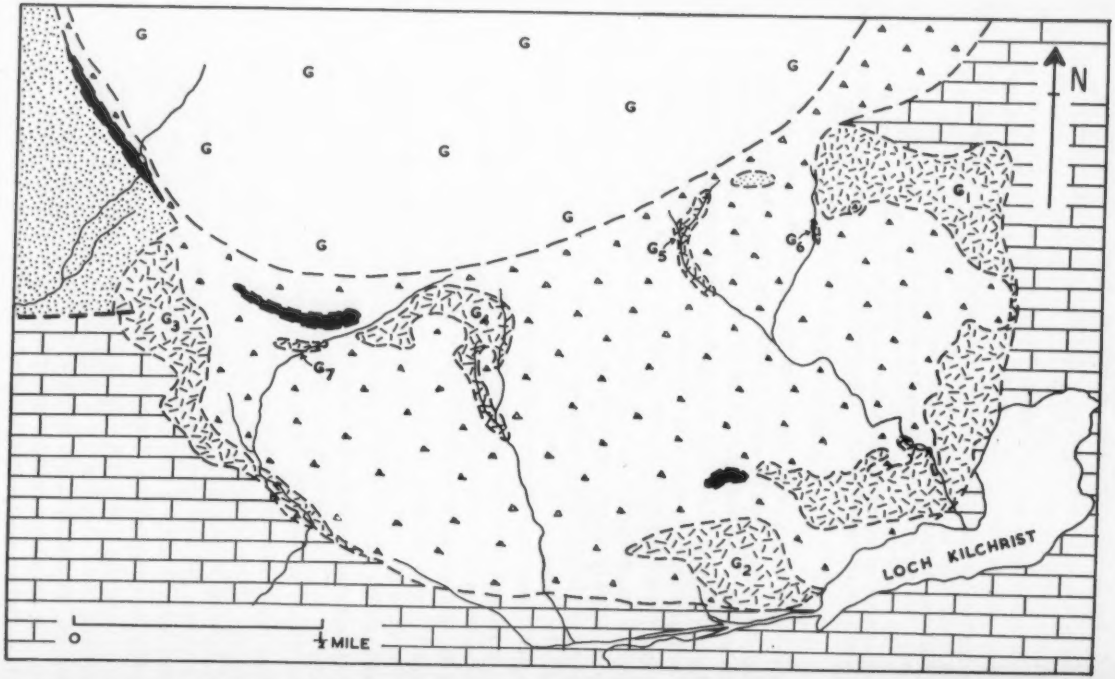
Introduction

The Kilchrist vent, situated about two and a half miles south-west of Broadford, is described by Harker (1904) in the Skye Memoir. The main infilling is agglomerate consisting predominantly of fragments of basic lavas, with less abundant fragments of sandstone derived from Jurassic and probably also from Torridonian rocks. Associated with the agglomerate are intrusions of " granophyre " occurring round the margin of the vent and as disconnected outcrops within it (Text-fig. 1). Harker (1896) found the " granophyre " to be locally margined against the agglomerate by felsitic rocks, some of them with fluxion-structure, which he thought to represent " the earliest irruptions of the acid magma ", irruptions which were separated from the coarser type both " in respect of time and of the circumstances attending intrusion ". During the present investigation it has been found that at least part of the flow-layered felsitic rocks is intrusive ignimbrite which is younger than the " granophyre ".

The term *ignimbrite* was coined by Marshall (1935) to describe New Zealand rocks composed of more or less devitrified shreds of glass which adhered together after they reached the ground and were therefore still hot and viscous after they fell. Marshall thought the glass shreds represented " minute fragments of volcanic magma " which had been transported as suspensoids in volcanic gases during eruptions of the " nuée ardente Katmaienne " type ; and he pointed out its similarity to Fenner's (1923) " indurated sand flow rock ".

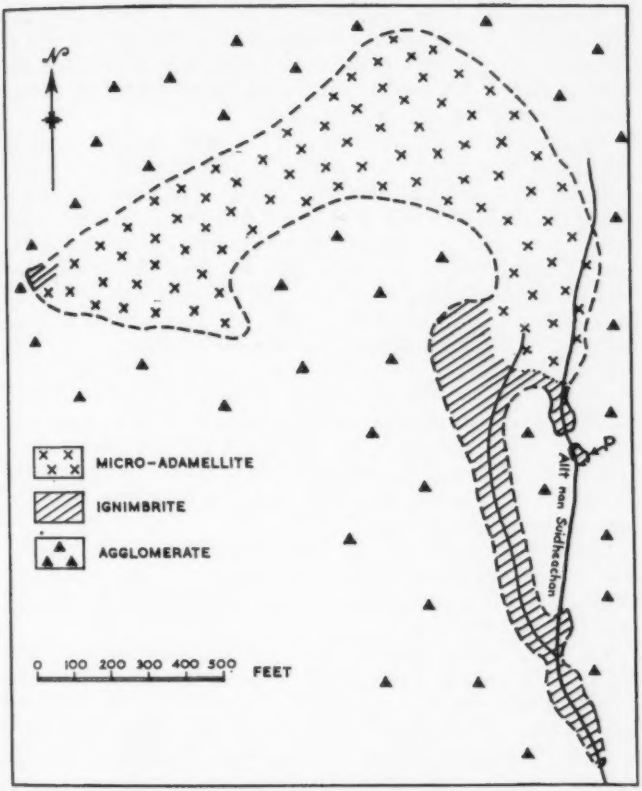
Although the term ignimbrite was introduced to describe extrusive rocks, it has since been used by Cotton (1944) and by Reynolds (1954) to describe similar rocks of intrusive origin. Cotton (1944, Fig. 102, p. 210) illustrates his account of the feeding channels of the New Zealand ignimbrites with a photograph of an ignimbrite dyke that was taken by Marshall. It was, therefore, eventually known to the originator of the term that ignimbrites occur as both extrusive and intrusive rocks.

In a Tertiary vent near Kilchoan, Ardnamurchan, Richey (1930, pp. 131–133) observed net-veins of a " light yellow compact material "



TEXT-FIG. 1.—General map of the Kilchrist vent, Skye, showing the position of the Allt nan Suidheachan mass, G4.

which Thomas (1930, pp. 139–140) found under the microscope to be "composed almost entirely of siliceous scoriaceous fragments and wisps of acid glass". These veins were subsequently described as



TEXT-FIG. 2.—The Allt nan Suidheachan mass, G4.

ignimbrite, with photographic illustrations, by Reynolds (1954, Plate I, *A* and *B*, p. 590).

The purpose of this paper is to describe another Tertiary example of intrusive ignimbrite occurring in the Kilchrist vent in Skye, where it forms part of the acid rocks of the Allt nan Suidheachan mass, outcrop G4 on Text-fig. 1. Intrusive ignimbrite has also been found in the outcrop G6.

The Allt Nan Suidheachan Mass (G4)

Field Relations

The mass G4 on Text-fig. 1, which forms high ground, includes two distinct rock types. As shown on Text-fig. 2, micro-adamellite (i.e., Harker's " granophyre ") occupies much of the northern part of the mass and ignimbrite occurs at the two extremities, its most extensive outcrop being to the south of the micro-adamellite along the narrow stream valley of the Allt nan Suidheachan.

Macroscopically the ignimbrite of the main outcrop varies in appearance from xenolithic rhyolite with flow layering to indurated acid tuff with abundant accidental debris. The ignimbrite matrix varies in colour from pale grey or buff to pale mauve, with darker streaks formed by still recognizable pumice lapilli which vary in size and are usually lenticular in form. Here and there within these lapilli vesicles, partially closed and drawn out into dark lines which run parallel to the long axis of the lenticles, are discernible on polished surfaces. Within the ignimbrite matrix basic xenoliths, derived from the vent agglomerate, occur as angular to sub-rounded forms which range in size from 4 cm. downwards. These xenoliths are unevenly distributed through the ignimbrite and are completely unsorted with regard to size. Occasionally they are drawn out into streaks which, like the pumice lapilli, are oriented parallel to the flow structure of the ignimbrite. Even apparently massive ignimbrite invariably shows flow structure on polished surfaces.

Like extrusive ignimbrites, the intrusive ignimbrite of the Kilchrist vent is well jointed. In the vent the ignimbrite is characterized by three sets of mutually perpendicular joints, producing a well developed pseudo-columnar structure.

The actual contact between ignimbrite and vent agglomerate is exposed at a number of places, and the ignimbrite can be seen to be steeply intruded into the agglomerate. Near the contact the ignimbrite characteristically shows flow layering which at the immediate contact is invariably parallel to the contact plane, the irregularities of which it reflects.

At the south-western corner of the main outcrop of ignimbrite (Text-fig. 2) the contact between the latter and the vent agglomerate is exposed on the steep right bank of the stream. Here the contact dips at approximately 50° towards S.S.W. From a distance this contact appears to be sharp, but there is actually an intervening zone, between 6 and 8 inches wide, of fine-grained basic tuff ramified by veinlets of felsitic material. This zone has a sharp and even contact with the vent agglomerate but grades imperceptibly into the main body of the ignimbrite intrusion. In this intervening zone the felsitic veinlets form

a highly contorted structure with minute overfolds and sharp bends, but the overall orientation of the veinlets is parallel to the contact.

The contact between the eastern margin of the main outcrop of ignimbrite and the vent agglomerate is exposed for a distance of about 45 feet, where it is vertical and trends N.N.W.–S.S.E. Here the vent agglomerate forms a sort of low wall, about 3 feet high, to which a thin contact-layer of ignimbrite adheres. The latter is porous and contains small lumps of pumice and rare fragments of pitchstone and basalt scoriae. It also shows abundant oval cross-sections of lithophysae, the long diameters of which are about an inch and a half. Marshall (1935, p. 41 and Plate 65, Fig. 2) recorded the occurrence of lithophysae in the type ignimbrites of New Zealand from Te Toki Point on the east side of Lake Taupo.

A few feet away from the eastern margin of the main outcrop of ignimbrite, the vent agglomerate at several places has a thin veneer of pumiceous material (about 3 mm. thick) which may possibly represent cracks in the agglomerate along which the acid material intruded beyond the main contact. A few narrow dykes of ignimbrite, apparently not physically connected with the main intrusion, also occur in the agglomerate. The small patch of ignimbrite within the agglomerate (P in Text-fig. 2), with an outcrop measuring approximately 30 by 18 feet, has a steep contact which is highly irregular in detail. A marginal zone of the ignimbrite, only a few millimetres thick, contains abundant minute fragments detached from the agglomerate.

In the field the exposed part of the boundary between the ignimbrite of the main outcrop and the micro-adamellite (dotted line in Text-fig. 2) appears to be gradational. As the micro-adamellite is approached the flow structure in the ignimbrite gradually disappears, and within a distance of about 10 feet the ignimbrite apparently grades into the micro-adamellite. Thin sections of the contact rocks, however, show the micro-adamellite to be traversed by a few veinlets of ignimbrite. The micro-adamellite is also traversed by a small vein of ignimbrite near its eastern margin. This evidence shows that the ignimbrite is younger than the micro-adamellite, and not older as Harker supposed.

The ignimbrite of the small outcrop at the western extremity of the micro-adamellite (Text-fig. 2) does not show flow structure. It is pale-cream or buff coloured and its porous matrix includes rounded fragments of older acid tuff and of pumice (Plate VII, fig. 1). It has a steep boundary against the vent agglomerate, but its contact with the micro-adamellite is not exposed.

Petrology

The ignimbrite is composed of abundant crystals of microperthitic potash feldspar ($\beta = 1 \cdot 526$) and subsidiary quartz crystals set in a

matrix composed essentially of devitrified shreds of glass that are firmly welded together. The potash feldspar and quartz occur as more or less corroded and embayed relics of euhedral crystals which vary in size between 0·3 and 2·5 mm. The feldspar crystals are sometimes surrounded by a narrow rim of fibrous feldspar in which the fibres grow normal to the margin of the core crystal. The fact that a broken crystal of potash feldspar is surrounded by a rim of this kind shows that the rims were formed at a late stage in the evolution of the rock. In twenty-two feldspar crystals examined on the universal stage the orientation of the optic axial plane was determined by reference to the composition plane (010) of Carlsbad twins. The orientation of the optic axial plane was found to vary from approximately parallel to (010) to approximately perpendicular to (010).

The ignimbrite outcropping to the west of the micro-adamellite (Text-fig. 2) is composed of typical glass shards such as are formed by the disruption of viscous pumice. The shards near xenoliths are somewhat elongated parallel to the xenolith margin and thus give rise to a laminar texture (Plate VII, fig. 1). In the ignimbrite of the main outcrop to the south of the micro-adamellite, however, the devitrified glass shreds are generally lenticular in form and invariably outlined by brownish opaque dust (Plate VII, fig. 3). In sections cut normal to the megascopic flow-layering these shreds appear spindle-shaped in cross-section, the axes of the spindles being directionally aligned parallel to one another to give rise to the flow-layering. The spindles overlap one another and present a dove-tailed appearance. At the immediate contact against agglomerate and near the margins of xenoliths derived therefrom the spindle-shaped or tapering shreds are plicated and variously folded. Similar distortions of shreds occur wherever there is a sudden change of trend of the flow-layering. Away from the contact, however, the shreds invariably curve round the margins of quartz and feldspar crystals and converge in the gaps between them as in extrusive ignimbrites. Marshall (1935) classified the New Zealand ignimbrites on a textural basis and used the term " lenticulite " to describe one variety. Since it is more useful to have a term with which to describe the texture rather than the rock in which it occurs, it is proposed that the texture here described be called *lenticulate texture*. The individual glassy or devitrified particles composing the lenticulate texture are not glass shards in the strict sense of the latter term, which is usually applied to " lune- or sickle-shaped pieces of glass " formed when " a number of contiguous or even coalescing bubbles (in highly viscous pumice) are forming and bursting at the same time " (Pirsson, 1915, p. 193), as in Plate VII, Fig. 1. From the fact that individual shreds sometimes show compressed bifurcating terminations (Plate VII, fig. 2), however, it can be recognized that at

least some of them originally had this form before they were drawn out in the direction of flow while still viscous.

Elongated pumice lapilli with tapering ends are associated with the devitrified lenticulate glass shreds and aligned with them. Some of the pumice lapilli have irregular edges made up of the concave outlines of disrupted gas cavities. In some cases the edges are drawn out at several points into minute " tongues " suggestive of dragging of plastic material during flow. The pumice lapilli contain vesicles in their central parts, sometimes one relatively big one. These vesicles and the disrupted marginal vesicles are bordered by lines of opaque dust, and by reference to such lines of dust it can sometimes be recognized that initial vesicles have been drawn out in the direction of the flow structure and partly or completely closed. This and the elongation of the lithophysae in the direction of the flow structure prove that at the time of the evolution of the lenticulate texture the pumice lapilli were still viscous and could be stretched without disruption of the vesicle walls. The temperature of the ignimbrite at the time of its emplacement was, therefore, not less than the temperature at which acid glass softens. Further evidence that the temperature was high is provided by basalt xenoliths derived, as noted by Harker, from the vent agglomerate. Some of these are elongated and their vesicles are drawn out into sinuous lines parallel to the trend of the flow structure in the matrix of the ignimbrite. Basalt, therefore, became viscous, indicating a temperature of the order of 1,000° C.

The initial glass shreds forming the matrix of the Kilchrist ignimbrite are devitrified in the same way as that described by Marshall from the New Zealand ignimbrites and by Gilbert (1938) from the welded tuffs in Eastern California. Feldspar fibres, both length-fast and -slow, extend normally inwards from the margins of the shreds, and the relatively larger fibres can be seen to taper out away from the margins. Marshall (1935, p. 23) used the term " pectinate " to describe this kind of comb-like devitrification texture. In the Kilchrist ignimbrite, as in those of New Zealand and Eastern California, the shreds showing pectinate texture characteristically have a core of granular quartz. Following Gilbert it is suggested that the fibres are potash feldspar elongated parallel to the *c*-axis with the optic-normal (*Y*) lying in the plane of symmetry, for only this orientation can give identical fibres with both positive and negative elongation. The thin walls of the lithophysae have devitrified in the same way as the glass shreds by a pectinate growth of feldspar fibres, the spaces between any two adjacent layers being filled with quartz growing inwards from the walls. In the bigger pumice lapilli the long central vesicle is usually only partially filled with granular quartz and is flanked by feldspar fibres which grow from either side of the lines of drawn-out collapsed vesicles, so that

several parallel rows are formed. A few of the relatively bigger shreds also have a partially filled central cavity. The similarity of the central cavities in the shreds to those in the pumice lapilli suggests that the former also were drawn out during emplacement.

As the micro-adamellite is approached the lenticulate texture gradually disappears and is replaced by a patchy microgranular texture. In places traces of the original lenticulate texture are preserved. Nearer the micro-adamellite the microgranular growth is gradually replaced by minute spherulites, both simple and two-ply, which are enclosed within areas of clear quartz with undulose extinction. Next, irregularly shaped multiple spherulites are developed in the ignimbrite. Finally, the rock is largely made up of interfering segments of radiating or arborescent sheafs of feldspar with interstitial lace-like quartz.

The Origin of the Flow Structure.

Above a thin basal layer of incoherent particles consisting of volcanic glass and crystals of feldspar and quartz, the lower parts of individual sheets of the New Zealand ignimbrites are composed of shreds of devitrified glass that are in general aligned with their long axes horizontal. This alignment of the shreds of glass, and their bent forms around the corners of the crystals, Marshall attributed to compression due to the weight of overlying pyroclasts. Earlier observers had supposed this structure to be flow structure but, as Marshall points out, mass flow would have entirely destroyed the form of the glass shreds and drawn them out into much longer streaks.

Since then other workers have traced the gradational change downwards from a vitroclastic to a eutaxitic or a pseudo-bedded (Enlows, 1955) texture in many heterolithic (Martin, 1959, p. 396) ignimbrite deposits. They have agreed with Marshall that increasing compression due to a progressively greater overburden results in the end in complete "elimination of pore space and complete accommodation of one fragment to another" (Mansfield and Ross, 1935). Even at this stage, however, individual shards usually attest to their original curved or bifurcated form and *random* orientation (see Plates 4, 6, 8 in Mansfield and Ross, 1935).

In the intrusive ignimbrites of Kilchrist, the laminar structure to which the orientation of the glass shreds gives rise is parallel to the highly inclined intrusive contacts which it follows in detail (see p. 232). The orientation of the glass shreds is, therefore, best explained as a consequence of some form of flow, and flowage was upwards and parallel to the walls. Further evidence that the alignment of the devitrified glass shreds is a flow structure is provided by veinlets of ignimbrite which in places traverse the ignimbrite outcropping to the west of the micro-adamellite. The veinlets are composed of minute

spindle-shaped shreds welded together with their long axes oriented approximately parallel to the vein boundaries. That the alignment of the shreds in the veinlets results from flow is indicated by these facts : (*a*) the parallelism of the shreds to one another and to the trend of the vein ; and (*b*) change of trend of a vein is accompanied by a similar change of trend of the constituent shreds. Since, as Marshall points out, mass flow in the ordinary sense of flow of a continuous liquid would have destroyed the detailed structure of the glass shreds composing the ignimbrite, it is suggested that they flowed as a disperse phase in gas, by which they were transported (Fenner, 1923, 1937 ; Reynolds, 1954), and that they were emplaced while they were still hot and viscous, and were drawn out by gas expansion in the direction of flow. It is further suggested that the parent acid melt, whatever its origin, was disrupted into droplets either by the through-passage of volcanic gas or by the sudden liberation and expansion of occluded gas. With an appropriately rapid velocity of flowage, the gas would transport the gas-charged droplets upwards along fissures in the vent agglomerate, and the droplets would become elongated in the direction of relief of pressure, i.e. in the direction of flow. The fact that fragments of basalt derived from the vent agglomerate were sometimes softened and oriented with the rest of the material during intrusion shows that the temperature was high enough for the droplets to undergo such plastic deformation.

As in the extrusive ignimbrites, the well developed joint system indicates that after its emplacement the ignimbrite cooled slowly. Slowness of cooling is further indicated by the extensive devitrification of the glass shreds. This suggests that after emplacement gas continued to escape through the ignimbrite. That stresses were set up by a struggle for space, after or during emplacement, is suggested by the fact that near xenoliths the lenticulate shreds are plicated as if by drag effects. Tight micro-folds are formed in which the shreds at the core are intricately twisted or concertinaed, while those away from it are progressively less deformed. The shreds behaved in the same way as the constituent units of a sedimentary fold-system.

Acknowledgments

I wish to express my gratitude to Professor A. Holmes, F.R.S. and Professor F. H. Stewart for allowing me to carry out the laboratory work involved in the investigation at the Grant Institute of Geology, University of Edinburgh. I would like to thank Dr. Grace Dunlop for her help during preparation of the paper. I also owe my thanks to Miss Jean Tarrant for taking the photomicrographs which illustrate the paper. A research grant from the University of Edinburgh covered the cost of ten weeks' field work in 1957 and is gratefully acknowledged.

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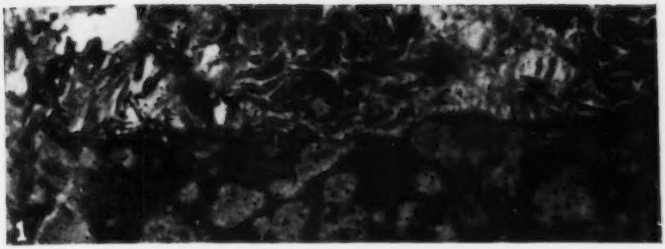
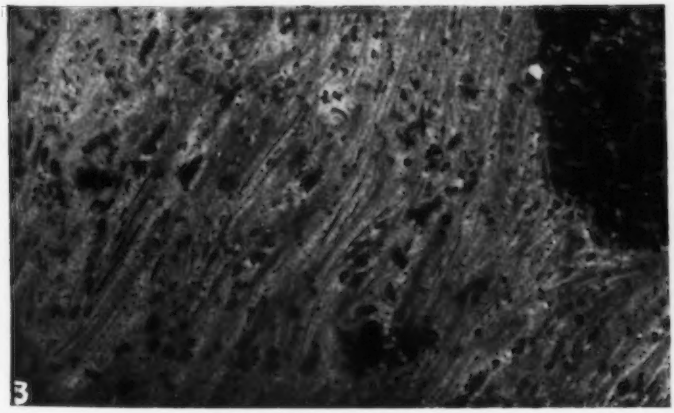
EXPLANATION OF PLATE VII

FIG. 1.—Ignimbrite from the small outcrop to the west of the micro-adamellite of G4 (Text-fig. 2). The upper part of the field illustrates ignimbrite composed of devitrified glass shards formed by the disruption of pumice. The lower part of the field shows part of a fragment of acid tuff which is enclosed in the ignimbrite. Immediately adjacent to the tuff fragment the shards are aligned parallel to its margin and slightly elongated × 30.

FIG. 2.—Ignimbrite, from the main outcrop to the south of the micro-adamellite, showing flow layering. The original cuspate form of the slightly elongated shards can still be detected × 40.

FIG. 3.—Ignimbrite, from the same locality as Fig. 2, showing typical lenticulate texture. The texture results from the marked elongation of devitrified glass shards, in the direction of flow, so that they become spindle-shaped shreds. The flow is deflected around a xenolith of basalt in the upper right-hand corner of the field, and some of the lenticulate shreds of devitrified glass are bent against the basalt × 40.





IGNIMBRITE IN THE KILCHRIST VENT, SKYE

Facing p. 238.

A Note on the Disposition of Fold Axes in the Silurian Strata around the Newry Granodiorite

By T. B. Anderson, D. E. B. Bates, and R. S. Hamilton

Abstract

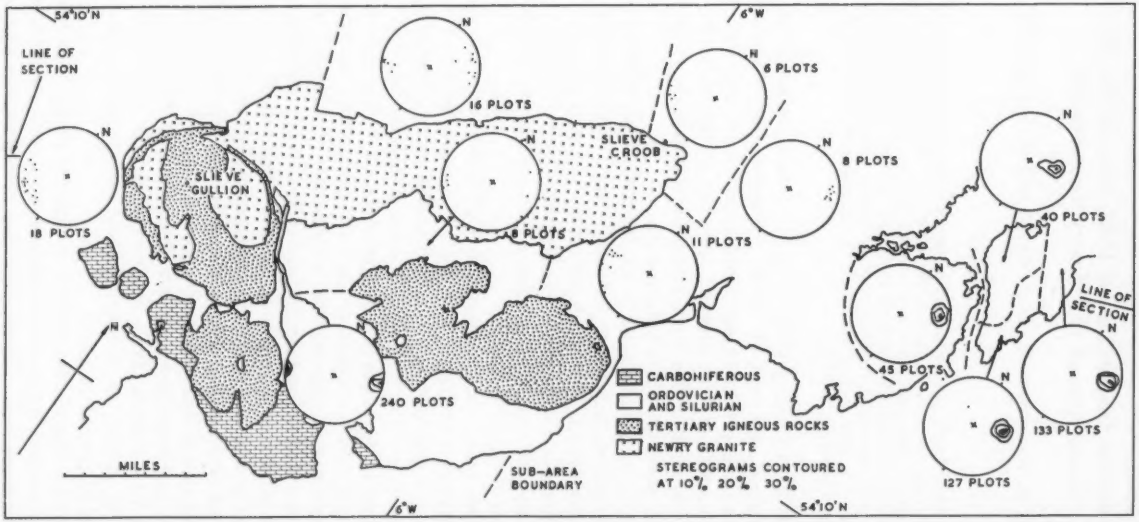
An area of high, north-eastward plunge of b-axes has been mapped in Silurian greywackes around the mouth of Strangford Lough, N. Ireland. Reconnaisance over a wider area to the south-west is consistent with the hypothesis that this steep plunge is due to the upward push exerted during the emplacement of the Newry Granodiorite. A near surface extension of the intrusion towards the east-north-east is inferred.

A SURVEY of folding of the Silurian greywackes around the mouth of Strangford Lough, Co. Down, has shown zones of abnormally high regional plunges. Investigation of fold axes over a much wider area was later carried out in an attempt to establish an explanation for this plunge. The result of this work, and the conclusions drawn from it, are given in the map and the following text.

The Silurian greywacke suite, which forms the Irish counterpart of the central belt of the Southern Uplands, is well exposed along the sea coast of Co. Down. The rocks are mainly blue-grey siltstones and slates, with some sandstones and a very small proportion of purple and green mudstones. The only fossils found are monograptids of Gala age, from a thin band of black shales.

The strata have been compressed by Caledonian earth movements into numerous close folds, the wavelength of which varies from about a metre up to a maximum of about five hundred metres. The fold axes trend between 30°–210° and 90°–270° and the folds are isoclinal. The plunge of the fold axes can be measured easily and accurately along the coast, but the outcrops inland are poor and consequently estimates of fold plunges are fewer and somewhat less accurate. Measurements of the intersection of bedding and cleavage and of the axes of micro folds have been used in the latter case as it can be shown that they are parallel to the major fold axes in the better coastal exposures. Close to the mouth of the Lough nearly all the fold axes plunge towards the east-north-east, over 90 per cent of them at angles between 15° and 60°. After folding two series of Lamprophyre dykes were emplaced. These have been described by Reynolds (1931) and connected with the Caledonian Newry Granodiorite, which outcrops about twenty miles to the west-south-west of Strangford Lough.

To facilitate analysis the country around the granite was divided into sub-areas each a few square miles in extent, and stereograms of plunges made for each. The sub-areas and stereograms are shown on



TEXT-FIG. 1.—Map of south Co. Armagh and south-east Co. Down showing the plunge of fold axes in the Silurian sediments. (Geological boundaries based on the Geological Survey of Ireland).

the map (Text-fig. 1). One of the most obvious features is the high plunge around the mouth of the Lough. The variation of plunge here represents a flexure of previously highly folded strata. Such a flexure might either reflect a fault at depth or drag associated with a fault offshore. In either case the fault would be approximately north–south in direction with an eastward downthrow, which would have to be very large indeed to explain the magnitude of the eastward plunge.

Although the evidence is scanty, Murphy (1932, pp. 24–25) tentatively suggests that Scrabo Hill, at the north end of Strangford Lough, is " the north-west extreme of a fault trough the main area of which is now covered with water " (i.e. Strangford Lough). He estimates its depth as three hundred metres at Scrabo. Such a fault would run approximately southwards towards the entrance of the Lough. It would be parallel to some fault valleys near the entrance and to faults just east of the main granodiorite outcrop. Parallel faults cut the Mourne and Slieve Gullion ring dykes.

There is also some evidence for the existence of an offshore fault. The most easterly exposures mapped have fold axes trending N.30°E., representing a considerable sinistral rotation, possibly fault drag, from the regional Caledonoid trend, although this suggests a horizontal rather than a vertical movement. Attention must also be given to the fact that in the extreme east the plunge is actually decreasing, and that the highest plunge readings occur between two and four miles west of this. If the plunge is due to drag against an offshore fault this feature is very difficult to explain.

An alternative hypothesis is that the high plunges result from the diapiric rise of a body of magma. Exposures of the Newry Granodiorite, although rather distant, are correctly aligned to explain the plunge in the area around the mouth of the Lough. The granodiorite has been described in detail by Reynolds (1934 and 1943) and she has inferred a change in direction of strike of the sediments due to magmatic pressure; and has stated that the biotite pyroxenite of the intrusion, at least, probably exerted a " shouldering stress on the sediments " (1934, p. 593).

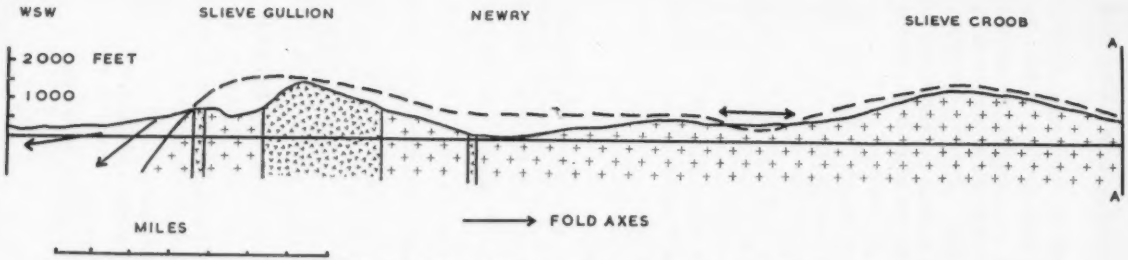
If doming by the granodiorite is the reason for the plunge, then the fold axes at the south-western end of the intrusion should plunge south-westwards. This was tested and found to be so, although the plunge away from the granodiorite only extends for about six miles from the contact, whereas the maximum plunge east-north-east of the granodiorite is fully eighteen miles from the contact. Plunges along the northern and southern edges of the intrusion tend to be low, which suggests that the fold axes are relatively undisturbed. This is to be expected as the doming should cause, if anything, a rotation around the

fold axes. Inliers of granodiorite north and south of the main outcrop suggest that the contact dips gently in these directions, and consequently the rotation would be slight. It is also possible that the rotational movement may have been taken up by dip-slip movements on planes parallel to bedding and cleavage.

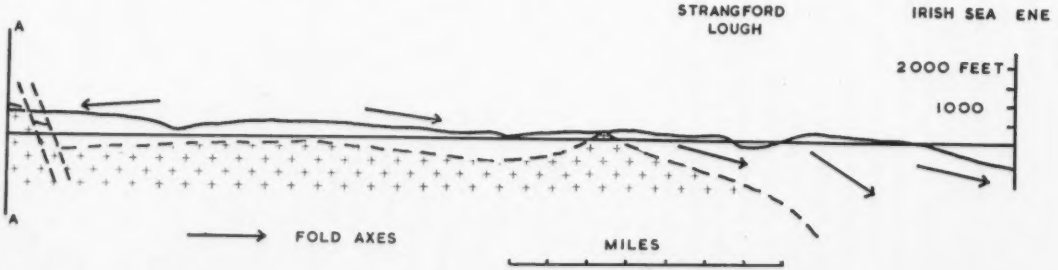
Throughout the area round the complex, few plunge readings were obtained to contradict the intrusion hypothesis. One notable exception is the small area on the north-eastern tip of the granodiorite, where fold axes plunge towards the contact, at about 13°, although this is known to dip east. It may be that, immediately adjoining the intrusion at this point, replacement or stoping has caused some sinking of the wall on the north-eastern corner. It is in any case clear that the Newry Granodiorite is a discordant body.

Reference to the map shows two plunge culminations. These may be regarded as points of maximum magmatic pressure. The two culminations, separated by a plunge depression, roughly correspond to the present topography, which is determined by the original shape of the roof of the intrusion (Text-figs. 2 and 3). The very high plunges at the mouth of Strangford Lough, and the lower plunges between this point and the contact, seem to indicate a sub-surface extension of the granodiorite east-north-eastwards, possibly downfaulted east of Slieve Croob as is indicated in the section (Text-fig. 3). This is contrary to Reynolds' interpretation of the north-eastern contact, which she believed to be nearly vertical, giving 64° to the east as the dip at one point (1934, p. 592). Outcrops of igneous rock, however, certainly occur east of the main contact, and a patch of Markfieldite actually outcrops about four miles west of the mouth of the Lough and about twelve miles east of the main intrusion (Patterson, 1942). These outcrops and the great abundance of Lamprophyre dykes along the line of the supposed extension, and striking parallel to it, seem to support our interpretation of the changes in fold plunge. The monoclinal steepening of plunge around the mouth of the Lough may indicate the north-easterly limit of the flatter portion of the roof of the intrusion. This eastern extension from Slieve Croob may be downthrown by the faults referred to earlier which would account for its concealment. The anomalous plunge of fold axes around the north-eastern contact is probably a local roof phenomenon.

Several objections may be made to the hypothesis outlined above. The correlation of maximum elevation of the granodiorite with the plunge culminations is not perfect. Unless, however, the plunge was uniformly zero before the intrusion, perfect correlation could not be expected. The correlation is none the less close and if the intrusion did not produce the plunge culminations, either an accidental coincidence has to be accepted, or both locus of intrusion and plunge culminations



TEXT-FIG. 2. N.E.–S.W. section through the Newry Granodiorite showing the plunge of fold axes in the Silurian sediments.



TEXT-FIG. 3.—Continuation of the section of Text-fig. 2 to the E.N.E. showing the subsurface extension of the Granodiorite.

must be attributed to a common cause such as cross-folding which seems improbable.

It may also be objected that no attention has been paid to the effect of the Tertiary intrusions of the Mourne-Slieve Gullion regions ; but if their mode of origin, as ring dykes with strongly transgressive margins, is accepted (Richey, 1932*a*), the effect on the attitude of the intruded rocks must have been very small. Richey states (1932*b*, p. 106), that at a point where the contact between the Silurian and the Tertiary intrusion is definitely not a fault, the strike of the Silurian beds has not been altered by the process of intrusion.

Geophysical evidence is, at the moment, lacking. There are a few gravity measurements around the granite (Murphy, 1952). These do not support the hypothesis of an east-north-east extension of the intrusion. The high density of the granodiorite, with its associated basic material, results in a low density contrast between the intrusion and the Silurian sediments, and a close grid of gravity measurements with a high order of accuracy will be necessary before trustworthy conclusions can be drawn. No very great importance can be attached to the few existing results.

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Ludlovian Biotite-Bearing Bands

By E. V. Tucker

Abstract

Allogenic biotite flakes, together with fish and conodont remains, are concentrated into bands at particular horizons within Upper Ludlovian rocks of Woolhope and other Welsh Borderland areas; and are present but more scattered within the Aymestry Limestone and *Dayia* Beds. Metamorphic rocks of Malvernian type appear to have provided the source of the biotite.

I. Introduction

Biotite-bearing bands within the Ludlovian rocks of the northern part of the Woolhope inlier (Herefordshire) have recently been recorded by the author (1958). This paper describes in more detail the character and significance of these deposits and the occurrence of similar bands in Ludlovian rocks of other Welsh Borderland inliers.

II. Occurrence and Lithological and Faunal Character

Within the Woolhope inlier, biotite is scattered throughout Ludlovian rocks of Aymestry Limestone, Mocktree (*Dayia*) Shale, and Upper Ludlow age. It is most abundant within thin bands in the middle of the Upper Ludlow (i.e. at or about the junction of the Lower and Upper Whitcliffe Flags). The term biotite-band is used in this paper for bands containing at least 5 per cent of biotite; although the percentage of biotite in many bands exceeds 25 per cent.

A typical biotite-band is exposed in the Upper Ludlow Beds (basal Upper Whitcliffe Flags) near Perton, outcropping at the laneside (SO 5970 4031) 3 to 4 feet below a prominent, 1 foot thick, calcareous siltstone band. At this locality the biotite-band is persistent over the length of the section. Its maximum thickness is 2 inches, but the band thins to less than half an inch. Biotite is also present in the immediately adjacent horizons but rapidly decreases in amount away from the biotite-band. Lithologically this micaceous deposit is a moderate yellowish-brown (10YR 6/4 on the Rock Color Chart), fairly well-sorted, friable calcareous sandstone (average grain size 0·18 mm) with abundant flakes of biotite (approximately 30 per cent). In thin section sub-angular crystals of quartz and feldspar cemented with calcite are revealed. Feldspar is present as orthoclase and plagioclase but forms a low percentage of the rock; frequently it is weakly kaolinized. Small crystals of apatite may represent thin sections of micro-organisms.

Macro-fossils are not common in the biotite-band although leached specimens of typical Upper Ludlow forms are present, e.g. *Camarotoechia nucula* (J. de C. Sowerby), *Chonetes striatellus* (Dalman), *Dalmanella lunata* (J. de C. Sowerby), *Orbiculoidea rugata* (J. de C.

Sowerby), *Beyrichia* sp., *Keilorites* sp., and *Michelinoceras* sp. Microfossils are abundant, particularly conodont and fish remains. Conodonts are normally fragmentary and are frequently difficult to identify: typical Ludlovian forms are present, e.g. Distacodid conodonts, *Ozarkodina typica* Branson and Mehl, and *Spathognathodus primus* Branson and Mehl. Ostracoderms are represented chiefly by thelodont denticles, although acanthodian remains are also present. Other organic remains include horny fragments of *Sphenothallus* [*Serpulites*] *longissimus* (J. de C. Sowerby).

Breakdown of the biotite-band for contained micro-organisms enabled the biotite flakes to be released without unnecessary damage. These flakes are relatively large (average size 0·38 mm) with typically a hexagonal outline and lie parallel to the bedding plane of the rock. The flakes are little broken, well preserved, and relatively thick. The excessive thickness of many flakes increases their weight to such an extent that they settle out with fish remains and conodonts in a concentrated solution of bromoform.

Similar biotite-bearing bands occur within Ludlovian rocks elsewhere in the Woolhope inlier. At Hill Farm (Tarrington, 6173 3983) a friable sandstone at a similar stratigraphical horizon contains abundant biotite flakes. Conodonts are again common, but thelodont denticles are less abundant. A lane-section (5741 3735) through the Upper Ludlow (which has here thickened locally) at Mordiford reveals a number of biotite-bands in a similar stratigraphical position. Only the lowest bed (71 feet below the Ludlow Bone-bed), up to 2 inches thick, is lithologically identical to the biotite-band at Perton. In this band, however, conodonts and fish remains are less common. The other bands, present in the succeeding 24 feet, are thicker, more calcareous, and contain proportionately less biotite. Conodonts, thelodonts, and *Sphenothallus* fragments are still present and are sometimes common. Within one band pellets of green mudstone are present, suggesting (local) erosion during deposition. Biotite is again fairly common, though more scattered, in deposits equivalent to the basal Upper Whitcliffe Beds near Westhide (5899 4418). Scattered flakes are also present (associated with pebble-beds) in the basal *Dayia* Beds of Shucknall Hill quarry (5918 4310) and a road section (5782 3480) near Fownhope. They also occur in the topmost Aymestry Limestone of Perton quarry (5953 3993). Biotite has not been recorded from rocks of either Upper Llandovery, Wenlock, or Lower Ludlow age in the Woolhope inlier.

III. Relationship Between the Biotite-bands and the Bone-beds of South Woolhope

It is significant that bone-beds have recently been recorded from the Ludlovian rocks of the southern part of the Woolhope inlier at strati-

graphical horizons equivalent to those at which the biotite-bands occur. A number of bone-beds are present at or about the junction of the Lower and Upper Whitcliffe Flags (Squirrel, 1958, p. 329), i.e. at the same horizon as the biotite-bands of Perton, Mordiford, and Hill Farm (Tarrington). Another bone-bed is developed immediately below the base of the Upper Ludlow in the south of the Woolhope inlier (op. cit., p. 329). A typical biotite-band is not present at this horizon in the north of the inlier (although scattered biotite flakes are present) and a thin pebble-bed appears to be the equivalent deposit. Thelodont denticles are also recorded from the basal *Dayia* Beds of south Woolhope, deposits the age-equivalent of biotite-bearing rocks in the north. It appears therefore that the bone-bed horizons of the south (where biotite is rare or absent) can be correlated with biotite-bearing bands (fish denticles sometimes common) in the north.

IV. Conditions of Deposition

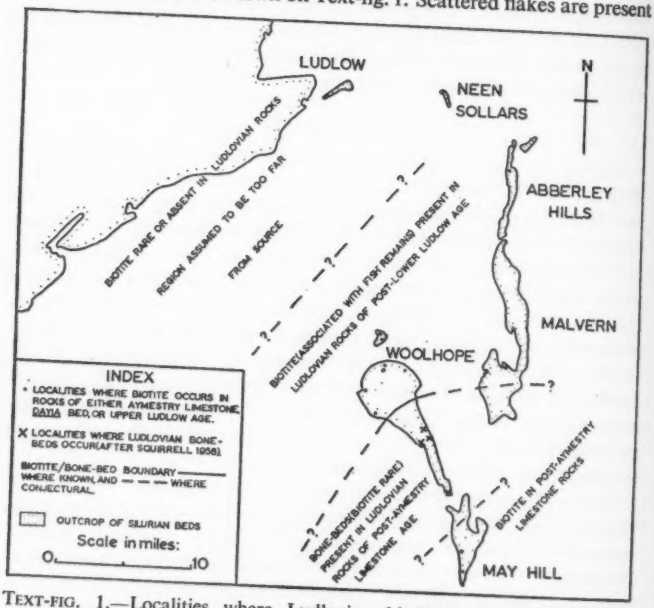
During the Ludlow period, and the Upper Ludlow in particular, the Welsh Lower Palaeozoic geosyncline was rapidly being infilled and the late Ludlovian deposits of the shelf-facies were accumulating under relatively shallow water conditions. Within the Woolhope inlier there is considerable evidence which supports such a depositional environment, bands of fragmented shells, pebble-beds, and small-scale contortions of the laminae being fairly common. Sedimentation therefore occurred in disturbed waters on a slowly subsiding sea floor. Subsidence in the north of the inlier proceeded more rapidly than in the south, the Ludlovian sequence becoming attenuated towards the south, where the succession is incompletely represented. The depth of water was probably always greater in the north than in the south, with correspondingly less-intense wave and current action.

Bone-beds are condensed deposits which accumulated under wave or current action, fine-grained detritus being winnowed away to leave fish remains in the residual fraction. By analogy with bone-bed formation, the presence in the biotite-bands of organic and inorganic elements with a high specific gravity, the uniformly coarse nature of the deposits, and the lack of calcareous invertebrate shells, all suggest a similar origin for the Ludlovian biotite-bands. The biotite flakes are thought to be allogenic and were transported into this depositional area at least from Aymestry Limestone times onwards, being scattered throughout parts of the *Dayia* Beds and much of the Upper Ludlow. Periods of stillstand or of less rapid subsidence would result in increased wave or current action, with the concentration of fish denticles, conodonts, miscellaneous organic remains, and biotite flakes into thin bands. However, in the shallower water of south Woolhope current action appears to have been too intense for the biotite flakes to remain and they were transported

northwards into somewhat deeper water where the current velocity decreased and the biotite settled, together with fish remains and conodont fragments. The periods of stillstand appear to have been gradual and pulsatory processes, this being reflected by the deposits above and below the biotite-bands (see p. 245) and by the scattered distribution of the biotite-bands themselves.

V. Other Occurrences of Biotite-bands

The association of biotite and Ludlovian rocks is not restricted to the Woolhope inlier; other occurrences in the south-eastern part of the Welsh Borderland are shown on Text-fig. 1. Scattered flakes are present


LUDLOW
NEEN SOLLARS
N
ABBERLEY HILLS
MALVERN
WOOLHOPE
MAY HILL
BIOTITE RARE OR ABSENT IN LUDLOVIAN ROCKS
REGION ASSUMED TO BE TOO FAR FROM SOURCE
BIOTITE ASSOCIATED WITH FISH REMAINS PRESENT IN LUDLOVIAN ROCKS OF POST-LOWER LUDLOW AGE
BONE-BEDS (BIOTITE RARE) PRESENT IN LUDLOVIAN ROCKS OF POST-AYMESTRY LIMESTONE AGE
BIOTITE IN POST-AYMESTRY LIMESTONE ROCKS
INDEX
• LOCALITIES WHERE BIOTITE OCCURS IN ROCKS OF EITHER AYMESTRY LIMESTONE DATA BED, OR UPPER LUDLOW AGE.
X LOCALITIES WHERE LUDLOVIAN BONE-BEDS OCCUR (AFTER SQUIRRELL 1958)
BIOTITE/BONE-BED BOUNDARY ——— WHERE KNOWN, AND — — — WHERE CONJECTURAL.
OUTCROP OF SILURIAN BEDS
Scale in miles:
0 10

Text-fig. 1.—Localities where Ludlovian biotite-bands and Ludlovian bone-beds are exposed in the Welsh Borderland.

in the middle of the Aymestry Limestone of Woodbury quarry (Abberley), and in the basal *Dayia* Beds of both the May Hill (SO 694 167) and Usk (SO 378 002) inliers, whilst biotite-bearing bands very similar to those of Woolhope occur towards the top of the Upper Longhope Beds (Upper Ludlow) in the May Hill (691 189) inlier, 30 to 40 feet below the Ludlow Bone-bed in the Malvern–Ledbury area (SO 7391 4095) and some 30 feet below the Ludlow Bone-bed at Woodbury quarry.

VI. Source of the Biotite

The vast quantity of biotite required for such deposits could have been derived only from igneous or metamorphic rocks. Exposures of pre-Silurian, biotite-rich igneous and metamorphic rocks in the south-eastern part of the Welsh Borderland are now confined to the Malvern Hills, although similar rocks undoubtedly form the basement of much of this area. The major outcrop of these rocks occupies the core of the Malvern range, the rocks being known locally as the Malvern Schists and Gneisses and the Warren House Volcanic Series. The former include biotite-hornblende schists which are themselves intruded by a number of thick pegmatitic veins and dykes in which biotite is abundant. These or (more probably) similar rocks appear to be the source of the biotite which was transported into this part of the Welsh Borderland in Ludlovian times.

VII. Conclusions

Friable sandstones with abundant biotite flakes, together with fish remains and conodonts, are assumed to have accumulated under the winnowing action of waves and currents. They can be correlated with bone-beds in the southern part of the Woolhope inlier. The occurrence of similar biotite-bands elsewhere in the Welsh Borderland points to a widespread influx of biotite into the Ludlovian sea. Only in the Pre-Cambrian igneous and metamorphic complex of the Malvern Hills are biotite-rich rocks exposed and these or similar rocks are assumed to have provided the source for this material. The increased abundance of biotite at particular horizons in the Ludlow points to its potential use in, at least local, correlation throughout the south-eastern part of the Welsh Borderland.

Acknowledgments

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Structural Behaviour of Quartzite in a Migmatite Area, Tanganyika

By P. E. Brown

(PLATE VIII)

Abstract

Quartz-magnetite rocks occur as lenses in an area of migmatitic mica gneiss and have acted as resisters to deformation as well as migmatization. Due to plastic deformation in the enclosing gneisses a quartzite lens now strikes perpendicular to the trend of other resisters which are abruptly truncated.

In the following note certain anomalous structural relationships between various resisters in a migmatite area are described and attributed to plastic deformation. The area is in the Southern Highlands Province of Tanganyika and is named after the native village of Igawa, on the Great North Road eighty miles east of the Provincial Town of Mbeya. Mapping was carried out as part of the regional programme of the Geological Survey and a general account of the geology of the area has been prepared (Survey Bulletin in press). On the basis of lithology, metamorphic history and strike directions the Igawa metasediments and migmatites are grouped by the Survey with the Ubendian rocks of western Tanganyika (see Sutton, Watson and James, 1954).

To the east of Igawa there is a north-south trending belt of mica gneiss which is transitional on its eastern border to porphyroblastic microcline granite. The gneisses are medium to coarse grained with variable quartzo-feldspathic content and range from finely banded to rather massive. They have in part undergone, migmatization. Typical specimens contain biotite, muscovite, quartz, oligoclase, small amounts of microcline, accessory epidote, iron ore, apatite and very rarely zircon, garnet and tourmaline. The plagioclase is usually sericitized and sieved by quartz; sutured grain boundaries and myrmekite are common. There are also subordinate quartzose and pelitic varieties. Quartz-oligoclase lamellae are common, usually parallel to the foliation; these lamellae are often bounded by biotite rich margins and sometimes contain muscovite-sillimanite (fibrolite) complexes.

Lenses of quartzite, up to a mile and a half in length, occur in the mica gneiss. Typical examples occur where the Mbarali River crosses the outcrop of the mica gneiss and on Chahuza Hill (see sketch map, text-fig. 1). They are medium grained, banded, black coloured rocks with rusty weathering and are extremely tough. The dark colour and banding are due to a variable content of magnetite; garnet is also frequently conspicuous in hand specimen. Thin sections show that the

quartz is in elongated grains with complex sutured boundaries and that the iron ore is either in laths or as a fine dust. As well as garnet the accessory minerals include diopside, epidote, rare tremolite and white mica. Less common types are richer in garnet, epidote and diopside and grade into metacalcareous bands.

Similar quartzites occur elsewhere in the basement rocks of Tanganyika, for example on the Lupa Goldfield (Grantham, 1932) and have also been mapped by the writer between the Lupa and the Mbeya Mountain Range. The Lupa rocks contain an iron amphibole, either grunerite or cummingtonite, commonly after pyroxene.

Prior to attaining their present grade of metamorphism quartzites of this type were almost certainly chert beds of a similar type to those described by James (1955) from the " iron formation " in the Lake Superior region, or the Indian banded hematite-jasper rocks described by Spencer and Percival (1952). They have been referred to previously as banded ironstones (e.g. Grantham, 1932) but in their present metamorphic condition the name ferruginous quartzite, which was used in the field, seems preferable.

Bounding the area of mica gneisses and ferruginous quartzites on the west is a discontinuous north–south trending ridge of marble which in places carries abundant epidote, garnet and diopside. Two narrow bands of schistose amphibolite, one of which is associated with a thin ferruginous quartzite, outcrop parallel to the marble and on its east side.

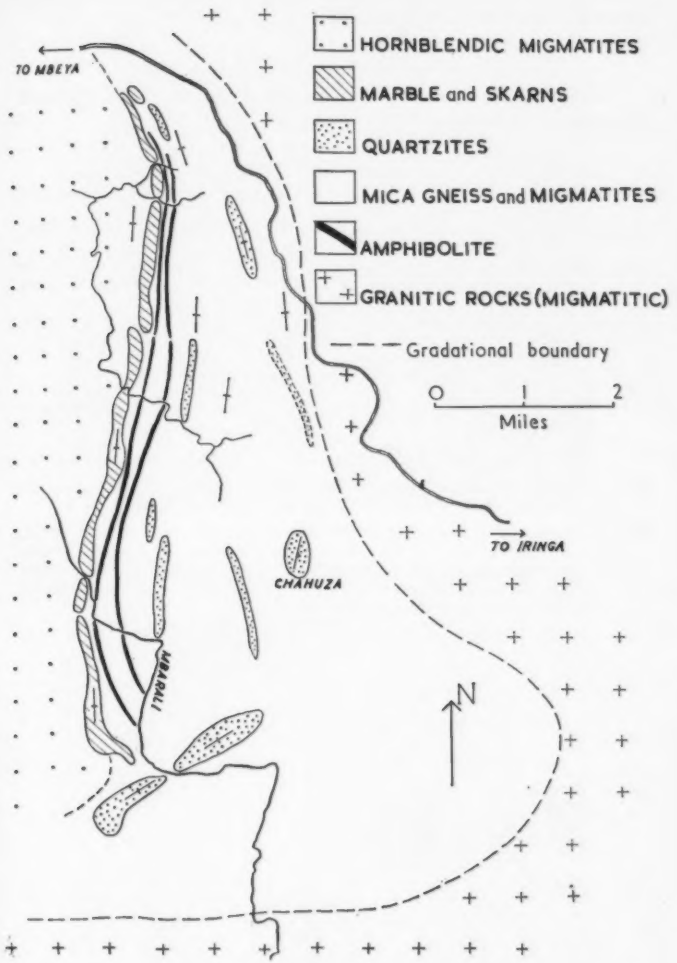
The strike of the mica gneisses over the greater part of the area is roughly north–south, the foliation being usually approximately vertical and little disturbed by flexure or contortion. Some small scale isoclinal folds have been observed and occasional isolated fragments of more competent quartzose bands indicate that isoclinal folding is probably general. The marble also has approximately vertical foliation and has been elongated into lenses. For example where the Mbarali River crosses the strike of the marble there are extensive exposures of migmatitic hornblend gneiss and amphibolite but the marble itself has been squeezed out.

In the south of the area the mica gneisses are bounded by an east-west trending zone of transition to migmatitic granodiorite. The swing from north-south to east-west trending contact with the granitic rocks is accompanied by intense deformation and crumpling of the foliation in the gneisses (Plate VIII, fig. 1). The area of strong deformation is also one of strong migmatization. There are excellent exposures of these rocks along the course of the Mbarali River. Where the marble approaches the area of greatest deformation in the mica gneisses it has undergone quartzo-feldspathic injection and is intensely altered to epidote-garnet-diopside skarns which, after outcropping as a strong

physical feature, terminate very abruptly. The two amphibolite bands and associated thin ferruginous quartzite, which lie just east of the marble, likewise terminate very abruptly. Their outcrop may be traced up to the western bank of the Mbarali, which here flows roughly south to north, but they do not reappear on the eastern bank (see text-fig. 1). This cut-off is not due to post-migmatization faulting. Two large lenses of ferruginous quartzite, separated by a narrow gap through which flows the Mbarali, occur just to the south. These quartzites strike E.N.E. almost perpendicular to the trend of the marble and amphibolites. The foliation in the quartzites is vertical and uncontorted in striking contrast to the mica gneiss which surrounds them. Excellent water washed exposures in the gap cut by the river show that the two quartzite lenses are due to elongation of a single lens parallel to its strike. Between the two main quartzite bodies there are isolated blocks of quartzite from a few feet up to sixty feet in length and several yards in width, enclosed in a base of migmatized mica gneiss (Plate VIII, fig. 2). The foliation of the isolated blocks is always parallel to that of the parent quartzite bodies which would seem to indicate that the separation was due to stretching along the strike. Immediately adjacent to the quartzite blocks the enclosing mica gneiss is not contorted and its foliation is parallel to that of the quartzites. Prior to the period of migmatization and deformation the quartzite presumably possessed the regional north–south trend, but it evidently not only resisted migmatization but deformation as well, behaving as a rigid body while the surrounding gneiss was in a semi-plastic condition. The abrupt contrast in strike of the marble and the quartzite may be attributed to the competent behaviour of the latter at the time when the gneisses were deforming plastically. The deformation of the gneisses, E.N.E. orientation of the quartzite and stretching along its strike were probably brought about in relation to the development of the granitic rocks which occur to the south. The Mbarali River takes a remarkable course, with three abrupt changes of direction, to pass through the gaps between the quartzite and marble resisters.

Other quartzite lenses in the area, such as that forming Chahuza Hill, also have approximately vertical foliation parallel to that of the adjacent gneiss. It is not certain whether the majority of them are tectonic lenses or original stratigraphic intercalations. No evidence of fold closure was found at the terminations of any of the lenses. If they are tectonic then difficulty would be found in explaining the more or less continuous outcrop of the nearby marble, but if the rocks originated as cherts they might well be stratigraphic lenses modified by later movements.

The Igawa area is illustrative of contrasted styles of deformation in rocks undergoing synorogenic migmatization. The micaceous rocks



TEXT-FIG. 1.—Geological sketch-map of the area east of Igawa, Southern Highlands Province, Tanganyika.

underwent extreme plastic contortion while the quartzites resisted structural deformation and alteration.

ACKNOWLEDGMENTS

The above note is published by permission of Mr. A. M. Quennell, Director of the Tanganyika Geological Survey.

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EXPLANATION OF PLATE VIII

FIG. 1.—Water-washed exposure of contorted gneiss in the area where the Mbarali River cuts between two large quartzite lenses.

FIG. 2.—Exposure of a small quartzite body in the bed of the Mbarali River. Within the area of the photograph the strike of the surrounding gneiss is parallel to that of the quartzite. The strike of this and other small quartzite lenses is parallel to that of the larger parent bodies from which they have been derived.

FIG. 1

FIG. 2

GNEISS AND QUARTZITE, E. OF IGAWA, TANGANYIKA

Facing p. 254.

The Distribution of Radioactivity in some Fine-grained Igneous Rocks

By E. Hamilton

Abstract

The quantitative distribution of the alpha particle activity in rocks and minerals by nuclear emulsion techniques is applied to some exceptionally fine-grained rocks. The distribution of radioactivity is comparable to that observed in the coarser-grained rock types more suitable to nuclear emulsion studies.

In recent years studies in the distribution of radioactivity in igneous rocks have been described by Curie (1946), Picciotto (1949, 1952), and Hamilton (1957, 1959). Most of this work has concerned the distribution of radioactivity in medium-grained rocks as determined by nuclear emulsion methods. In this method ordinary thin sections of a rock are cut, and the surface slightly polished, the cover glass being omitted. The thin section is stored in a dust-free atmosphere for a period of one month to enable radioactive equilibrium to be restored. The thin section is then washed in demineralized water, and dried. A little Ilford G. Special (or C2 emulsion) is warmed in a beaker and when liquid it is poured over the rock section. It is then placed in a lightproof box and kept at $-4°$ C. for the exposure period of one month. At the end of this time the emulsion, in direct contact with the surface of the rock section, is developed and dried. The distribution of the alpha particle tracks are observed, using a $\times$ 53 objective and $\times$ 10 ocular binocular microscope fitted with a travelling stage. The alpha particle activity is registered in the emulsion as a composite black track composed of small clusters of silver grains. The length of the track is proportional to the energy of the alpha particle. The actual length of the track is determined by the amount of absorbing material that it has had to pass through before being registered in the nuclear emulsion above. Should the point source of the alpha particle be at such a depth in the rock section that the energy is totally absorbed, no alpha particle will be registered in the emulsion. In addition to the absorbence which takes place in passing through the mineral the nuclear emulsion also acts as an absorber.

This method of direct autoradiography is to be preferred to other methods in which a nuclear emulsion-coated, glass slide is placed in contact with a rock surface and then removed for developing.

The heterogenous distribution of radioactivity in the acid rocks in particular involves difficulties in sampling for emulsion studies. This can be partly overcome by exposing a large flat surface of the rock in contact with Kodak No-Screen X-Ray Paper. This large-scale auto-

radiograph will show whether or not the distribution of radioactivity is homogenous.

The grain size of a rock is an important factor in a quantitative study. Generally, the upper limit would correspond to a rock of medium grain size, and the lower limit to a rock on which a modal analysis can be carried out with reasonable accuracy. If the grain size is too small for any modal analyses, useful data on the distribution of radioactivity can still be obtained. As an example of the method applied to very fine-grained rocks, the following descriptions are given of the analyses of specimens from the Loch Ba felsite, Mhoire Choire trachyte, an oligoclase andesite from Hawaii, a trachyte from Hawaii, and two basalts from East Greenland.

(*a*) *Loch Ba felsite*

The Loch Ba felsite is a fine-grained rock, which varies between a rhyolite or felsite according to the amount of devitrification, and the presence or absence of dominant flow structures. It contains small phenocrysts of feldspar, and euhedral augite in a matrix showing various amounts of banding and devitrification. The particular specimen which was analysed consisted of a fine-grained crystalline portion and an adjacent zone of partly devitrified glass showing a flow pattern. The total autoradiographic analyses of both components are given in Table 1A, 1B.

The total radioactivity from the area of devitrified glass ($13{\cdot}0 \times 10^{-5}$ α/cm.^{2}/sec.) is very similar in order of magnitude to that from the area of granophyre ($14{\cdot}1 \times 10^{-5}$ α/cm.^{2}/sec.). In the analyses however a further division was made in that the radioactivity from the border zone of devitrified glass to granophyre was recorded. In this zone the total percentage of radioactivity to the total radioactivity from the felsite (crystalline area + devitrified glass) was as follows:—

	Per cent.
Feldspar	77
Quartz	84
Ore	70
Yellow areas	85
Intercrystal	55
Zircon	75
Other accessories	75

All cases greater than 50 per cent of the total radioactivity in the felsite were concentrated along the border area felsite/devitrified glass. The average radioactivity of the felsite portion was then reduced to $3{\cdot}6 \times 10^{-5}$ α/cm.^{2}/sec. In the devitrified glass a similar pattern was observed but because of the absence of minerals no quantitative analyses were possible.

TABLE 1.

1A. Area of devitrified glass.

Mineral	Total number of alpha tracks (1)	Percentage of the total activity from the glass (2)	Alpha activity α/cm.²/sec.
Brown glass	116	38·0	
Turbid feldspar	119	39·0	
Quartz	2	0·7	
Ore	23	7·5	$13{\cdot}0 \times 10^{-5}$
Yellow mineral *	24	7·8	
Pyroxene; biotite	2	0·7	
Accessories	15	4·9	
Intercrystal	4	1·4	
Total	305	100·0	

* Probably hydrated iron oxides and secondary ferruginous products.

(1) The actual number of alpha particles coming from each mineral.

(2) The ratio of the activity from each mineral to the total radioactivity.

1B. Granophyre area.

Mineral	Total number of alpha tracks	Mode-volume %	Percentage of the total activity from the granophyre	Percentage of the total activity from the mineral	Alpha activity α/cm.²/sec.
Feldspar * (total)	390	80·0	38·9	100·0	$6{\cdot}8 \times 10^{-5}$
Feldspar	9		0·9	2·3	$0{\cdot}2 \times 10^{-5}$
Inclusions	378		37·8	97·0	
Cracks	3		0·3	0·7	
Quartz (total	81	11·0	8·1	100·0	$84{\cdot}8 \times 10^{-5}$
Quartz	10		1·0	12·0	$9{\cdot}5 \times 10^{-5}$
Inclusions	71		7·1	88·0	
Cracks	0		—	—	
Ore alteration	79	5·4	7·9	100·0	$20{\cdot}6 \times 10^{-5}$
Yellow alteration	85	4·4	8·5	100·0	$27{\cdot}2 \times 10^{-5}$
Zircon	128		12·7	100·0	
Xenotime	76	0·3	7·6	100·0	1460×10^{-5}
Sphene	118		11·7	100·0	
Pyroxene			0·4		

Total radioactivity from the granophyric area $14{\cdot}1 \times 10^{-5}$ α/cm.²/sec.

* The feldspar includes some quartz.

Of the major minerals the bulk of the radioactivity is contained in inclusions of the major minerals. This is common in the more acid igneous rocks. The alpha particle radioactivity of the feldspar corresponds to a uranium content of 0·3 p.p.m.U., and the quartz to a uranium content of 29 p.p.m.U. assuming a U./Th. ratio of 1/3. The ore minerals in the area of devitrified glass are arranged as parallel bands corresponding to the original flow lines. The radioactivity from the ore, and yellow alteration products of the ore, are very similar. This suggests that the alteration has occurred *in situ*, rather than through the influx of later solutions. In addition, the radioactivity

from the ore in the devitrified and felsite areas is also similar. The actual source of the radioactivity is concentrated in peripheral areas indicating that the absorption of U, Th. is on the hydrated iron oxide surfaces. The accessory minerals are the most radioactive minerals present. The sphene is generally associated with iron ore and apatite.

The analyses of some fine-grained homogenous rocks

Analyses of a few of the olivine basalts, tholeiites, and trachytes studied are given as examples of these rocks.

(*a*) *Olivine basalt E.G. 1093* (*Table 2*)

The olivine basalt E.G. 1093 is described by Wager and Deer (1934) for which a chemical analyses is given. The analyses shows that the lava conforms to a type already known from the Tertiary basalt areas of the North Atlantic, and is similar to the Porphyritic Central Type as defined by the authors of the Mull Memoir.

TABLE 2.

Mineral	Total number of alpha tracks	Mode-volume %	Percentage of the total activity from the rock	Percentage of the total activity from the mineral	$\alpha/cm.^2/sec.$
Feldspar (total)	18	54	41·0	100	$1·3 \times 10^{-5}$
Feldspar	9		20·5	50	$0·7 \times 10^{-5}$
Inclusions	9		20·5	50	
Pyroxene (total)	5	31	11·4	100	$6·2 \times 10^{-6}$
Pyroxene	3		6·9	60	$3·7 \times 10^{-6}$
Inclusions	2		4·5	40	
Olivine	3	6	6·9	100	$1·9 \times 10^{-5}$
Ore	2	9	4·5	100	$9·0 \times 10^{-6}$
Intercrystal	12		26·8	100	

Total alpha radioactivity $1·7 \times 10^{-5}$ $\alpha/cm.^2/sec.$
Uranium content 0·25 p.p.m.U.

(*b*) *Tholeiitic basalt E.G. 1057* (*Table 3*)

This tholeiitic basalt has been described by Wager and Deer (1934).

TABLE 3.

Mineral	Total number of alpha tracks	Mode-volume %	Percentage of the total activity from the rock	Percentage of the total activity from the mineral	$\alpha/cm.^2/sec.$
Area of glass (total)	65	29	51·0	100·0	$8·5 \times 10^{-6}$
Ore	9		7·0	13·6	
Brown clear glass	19		14·9	29·6	
Turbid glass	29		22·5	45·6	
Inclusions	8		6·3	12·4	
Feldspar (total)	35	35	27·0	100·0	$3·8 \times 10^{-5}$
Feldspar	22		17·0	63·0	
Inclusions	9		7·0	25·5	
Cracks	4		3·0	11·5	
Ore	3	7	2·3	100·0	$1·6 \times 10^{-5}$
Pyroxene	3	29	2·3	100·0	$3·9 \times 10^{-5}$

Total alpha activity $4·94 \times 10^{-5}$ $\alpha/cm.^2/sec.$
Uranium content 0·66 p.p.m.U.

The increase of radioactivity in the areas of glass is characteristic of the tholeiitic basalts. In the rocks analysed generally 50 per cent of the total radioactivity originated from the areas of glass. The radioactivity of the major minerals in these rocks is higher than that of the major minerals from the olivine basalts.

(*c*) *Fine-grained alkaline rocks*

As an example to this type of rock a fine-grained facies of the Mhoire Choire trachyte was chosen as a rock on which a modal analysis was impossible because of the slender feldspar laths and the fine-grained minerals packed between the feldspar. In addition an oligoclase andesite (N3609 Haui volcanic series Macdonald, 1949) and a trachyte (J3606 Macdonald, 1949) were examined. Both the latter rocks were of extremely fine-grained size, a modal analyses being impossible. In these rocks it was only possible to determine the total alpha particle activity, and the relative amounts present in the different minerals.

TABLE 4.

Mineral	Mhoire Choire Trachyte		Trachyte J3606		Oligoclase andesite N3609	
	a	b	a	b	a	b
Feldspar (total)	113	40·0	137	64·6	58	58
Feldspar	23	8·0	63	29·6	12	12
Inclusions	90	32·0	74	35·0	42	42
Pyroxene	22	7·0	9	4·2	0	0
Amphibole	38	13·6	0	0·0	0	0
Ore	5	5·6	10	4·7	4	4
Intercrystal	44	14·8	16	7·5	4	4
Accessories ?	14					
Sphene, zircon	31	17·1	0	0·0	0	0
Apatite	3					
Groundmass	0		41	19·0	19	19
alpha/cm.^{2}/sec. $\times 10^{-5}$	6·7		5·2		2·3	

a—Total alpha particle activity.

b—Percentage of the total activity from the rock.

The distribution of radioactivity in these rocks is very similar to that found in other igneous rocks. It is significant that greater than 50 per cent of the total feldspar activity originates from inclusions within the feldspar. The total radioactivity of the rocks analysed shows an increase with silica and potassium content but not with sodium content.

The analyses are given in Table 5. Although the rocks are taken from widespread localities they show the same features of each

particular rock group. The tholeiilitic basalts are enriched in uranium relative to the silica and potassium contents. This type of enrichment is normally found in extreme differentiates and late stage members of igneous rocks.

TABLE 5.

Rock type.	α/cm.^{2}/sec. $\times 10^{-5}$.	SiO_2	K_2O	Na_2O	*References.*
Loch Ba felsite .	14·1	72·66	5·26	3·26	Bailey, *et al.*, 1924, p. 347.
Moire Choire trachyte.	6·7	63·12	5·36	5·81	Bailey, *et al.*, 1924, p. 191.
Trachyte J3606 .	5·2	62·02	4·93	6·90	Macdonald, 1949, p. 78.
Oligoclase andesite N3609.	2·3	52·27	2·22	5·40	Macdonald, 1949, p. 87.
Olivine basalt E.G. 1096.	1·7	47·26	0·81	2·30	Wager and Deer, 1934, p. 32.
Tholeiitic basalt 1057.	4·9	48·89	0·30	2·74	Wager and Deer, 1934, p. 32.

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CORRESPONDENCE

IMPREGNATION OF ROCKS FOR SECTIONING

SIR,—A procedure for impregnating rocks with resin in preparation for sectioning, which gives good results without the need for evacuation, is described below.

The resin used is of the polyester type and has the advantages of low viscosity (100 centistokes at 25° C.) and good wetting power in the initial liquid condition. It is manufactured by Bakelite Limited, of 12–18 Grosvenor Gardens, London, S.W. 1, under the designation DSR 19098. For rock impregnation the catalyst and accelerating agent usually employed to bring about polymerization are dispensed with, hardening being secured by prolonged heating carried out in two stages. The rock samples are first stood or submerged in the resin and heated to about 75° C. This initially lowers the viscosity, enabling the resin to penetrate by capillary action, but after some twelve hours the resin will be found to have become treacly or have gelled, and the temperature is then raised to about 125° C. for a further 12–24 hours. The resin should then have aquired a tough, rubbery consistency, and on cooling to room temperature, should be quite hard and slightly brittle. The samples are then ready for sectioning in the usual way. Times and temperatures quoted are only approximate and are best determined by experience, as the curing time at any temperature depends partly on the age of the resin and the degree to which it has been exposed to light and air.

The treatment is carried out in small metal trays (e.g., tobacco tins) and it is an advantage to cover or close them loosely to cut down evaporation. The polymerised resin does not adhere strongly to metals, so that the impregnated samples can be removed by gentle tapping and chipping. An ordinary laboratory oven is suitable for the hardening process, or if necessary a hot-plate may be used, with slightly inferior results.

Using this resin as described, good thin sections have been obtained from a loess, a chalky solifluction sludge, and a variety of unconsolidated Recent sands, silts, and clays, and exceptionally good sections from sub-greywackes and other rocks which, though on the whole well-cemented or compacted, often contain locally soft material liable to be plucked out during grinding.

The writer is indebted to Bakelite, Ltd., for samples and information, and to Mr. E. J. Hill, who cut the sections.

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FESTOON BEDDING AND "MUD-WITH-LENTICLES" LITHOLOGY

SIR,—Like Professor J. Sutton and Dr. J. V. Watson (*Geol. Mag.*, 1960, xcvii, 106–122), we have been struck by the beautifully preserved sedimentary structures in the Torridonian. On the mainland around Loch Torridon, the Diabaig and Applecross groups abound in exposures displaying small and large scale features quite as well preserved as any in the Weald. Particularly striking are the shore sections at Diabaig and the new exposures by the Alligin–Diabaig road.

Festoon bedding.—Sutton and Watson may be right in attributing, in general terms, their medium-scale festoon bedding (*cf.* Potter and Glass, 1958, *Illinois State Geol. Surv. Rep.* 204, pl. 1A) partly to deposition by "shallow, braided rivers" (p. 113). We infer that the bulk of the erosion and filling processes they envisage might have been carried out by underwater currents

(" streams ") during periods when the irregular (" braided ") bottom topography was completely submerged, whether or not it became exposed betweentimes. Their " channels " may thus represent mazes of shifting hollows or trenches and their " banks " impermanent hummocks between, completely submerged at high stage (or was it high tide ?). Formation of the stacked and interfering Torridonian structures, through the filling and abandonment of long subaerial channels repeatedly cut by neighbouring streams, seems a less likely mechanism. So also is that leading to the development of muddy festoons through the aggradation of intertidal gullies (McKee, 1939, *Journ. Geol.*, xlvii, 78–79 and pl. II).

Can the authors go further ? Have they seen, for instance, any large exposures showing the three-dimensional relations of groups of festoons, suggesting that these are actually worn-down *megaripples* ? It is interesting to know that the " dimensions of the troughs . . . remain fairly consistent in any single outcrop " (p. 110), for this we believe favours a ripple-like regularity. The work of Hülsemann (1955, *Senck. leth.*, xxxvi, 359–388) and others on modern sediments suggests that the march of " societies " of megaripples (accretionary hummocks preceded by erosional hollows) is an important process leading to the formation of festoon bedding. Each megaripple in its forward growth appears to deposit a single lens of festooned sand, and each society a stack of interfering lenses parted by erosional surfaces. The bases of adjacent lenses (floors of original hollows) normally intersect along sharp cusp-like ridges, as described by Sutton and Watson (p. 111). It may be more than mere coincidence that the range of breadths of the festoons ($<$ 1 m. to 6 m.) in the Epidotic Grits is rather close to the range of lengths along the crests of the megaripples figured by Hülsemann (fig. 1, pls. 2, 3). Megaripples form one of the most striking expressions of bed-movement within the braided channels of some swift sand-laden rivers (e.g. Benue and Niger, West Africa), as well as in many tidal inlets where water speeds are high (e.g. Friesian Islands ; German North Sea estuaries). Festoon bedding is thus not necessarily indicative of fluviatile sedimentation, nor does it always denote exposure of the sediments.

The examples in the Hastings Beds (Sussex coast and Mid-Sussex) appear to represent underwater " braided " mazes of either large shifting ripples or less regular hummocks-and-hollows near the mouths of major distributaries (*Phil. Trans. Roy. Soc.*, B, 1959, ccxlii, 320, 329). In particular the festoons in the Lower Tunbridge Wells Sand of Mid-Sussex are related to a channel coming southwards from the London Platform. The latter is even " visible " on Reeves's Lower Tunbridge Wells isopach map as a north–south belt of thinning (*Proc. Geol. Ass.*, 1949, lix, 259, fig. 31). Recent work on the different types of festoon bedding in the Lower Tunbridge Wells Sand shows that in Mid-Sussex the festoons are biggest at the top of the formation, where the sediment was more frequently exposed. Thus certain of the middle and upper sands (e.g. lane banks south-west of Hook Quarry, West Hoathly ; north side of B2110, between parish church and cross-roads, Turner's Hill) consist locally of festoon units a few feet across. Most of them fall within a narrow range of size, and occasionally inverted festoons (concordantly aggraded hummocks) are seen, even more obviously suggesting a megarippled bottom topography. At the very top of the sequence, the festooning consists of enormous " scoops " or " saucers " (" sand-waves ", " underwater dunes," mouth-bars ?) over 40 yds. long (*Proc. Geol. Soc. Lond.*, 1960, no. 1575, 27–28).

Mud-with-lenticles lithology.—This type of lithology (Sutton and Watson, 118, 120) may be seen on the shore section at Lower Diabaig, exposing the lower part of the Geological Survey's " dark shales and mudstones " (Peach *et al.*, *N.W. Highland Memoir*, 1907, 324). To us it suggests rhythmic (e.g. intertidal) conditions. The Diabaig lenticles are largely ripple-ridges, frequently isolated from one another on a muddy floor. In size and character they can be matched around our coast to-day where limited quantities of rippled silt or sand are moving across a muddy foreshore. Like the Skye lithology, that at Diabaig includes numerous beds with rainprints and

suncracks, the latter filled with coarser sandy or silty material. Again, fine discontinuous shale laminae, often broken, occur at the bottom of the overlying arkosic sandstones (*cf.* Sutton and Watson, text-fig. 7 (upper diagram)). Orientated particles of shale are also found on the foresets of coarser cross-bedded units having plane bedding and low depositional dips. Interbedded associations of the coarser and finer lithologies are found. Thus some of the finely laminated beds at Diabaig with small scale grading, ripple marking, and concentrations of grit particles in ripple hollows (*cf.* Sutton and Watson, 118) sometimes include coarser grit and sandstone bands.

These observations obviously invite comparison of the Diabaig group in Wester Ross with ordinary shallow water marine sediments, including intertidal deposits. One is not, of course, surprised to find that the older workers had considered this possibility. On page 325 of the N.W. Highland Memoir there occurs the following passage : " These facts point to shallow-water conditions, and the deposition of the sediment on a tidal shore . . ."

Speculation.—What is the significance of the drastic upward change to Applecross lithology and the (apparent) lateral change in facies between Wester Ross and Skye ?

Would it not be valuable to physicists and cosmologists to *know* there were tides in Scotland 1,000 million years ago ? Even, perhaps (shifting the emphasis to our mother star), that the sunspot cycle was operating merrily in Wealden times ?

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6th May, 1960.

THE OLD RED SANDSTONE OF EASTERN EKMANFJORDEN

SIR,—The sandstone members of the Kapp Kjeldsen and Lykta Divisions of the Old Red Sandstone described by Mr. D. L. Dineley (*Geol. Mag.*, xcvii, 18–31), appear to contain several sedimentary features generally regarded as characteristic of turbidity current deposits, and in view of the tendency to regard most " turbidites " as of deep water, marine origin, the present examples are of more than usual interest. Whilst marine turbidites have received much attention in recent years, following the work of Kueuen and others, it is perhaps worth recalling that some of the significant early work of the mechanism of turbidity currents and the resulting deposits arose from the study of sedimentation in lakes and reservoirs (Bell, 1942). The generation of turbidity currents in quiescent bodies of water by a mechanism comparable to " flash floods " may be particularly significant in relation to the environment of the Old Red Sandstone deposits here described, the majority of which appears to be of shallow water origin.

It would, therefore, be of considerable interest if certain of the sedimentary features possibly indicative of turbidity action could be confirmed. For instance, basal conglomeratic layers are stated to occur in some sandstone layers, but it is not entirely clear whether in fact these are true graded beds. The occurrence of intra-clast conglomerates and the concentration of fossils in them suggest the action of powerful currents and concomitant rapid deposition, and again grading (both lateral and vertical) of the beds might be expected.

In the sandstones of the Lykta Division contorted bedding and sole markings are described. The former appears to have many of the features ascribed to *intrastratal flowage* (Rich, 1950, p. 729) but perhaps may be more correctly attributed to *load casting* (Kueuen, 1953, p. 1058). The sole markings described and figured (*vide* page 26 and text-fig. 4) certainly appear to agree closely with

similar structures referred to as *groove casts* or *drag marks* (Kueuen, 1957, fig. 12, p. 244), and the fact that they occur only on the base of the sandstone beds would seem to argue against their being tectonic lineation.

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31st March, 1960.

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REVIEW

Beaches and Coasts. By Cuchlaine A. M. King. pp. 403 with 149 figures. Edward Arnold, London, 1959. Price 65*s*.

The author, an active worker on the subject, has written a comprehensive survey of our present knowledge of coastal sedimentation.

The earlier part of the book deals with the general background to the subject and includes sections on tides and wave motion (the latter at considerable length), and on methods of research, including model experiments in tanks. This is followed by an account of movement of material on the beach, which incorporates recent experimental and undersea observational work on such topics as sand ripples, longshore drift, grading and sorting, and an interesting section on the depth to which wave action is capable of disturbing sand.

Later chapters deal with beach profiles, effects of wind, the classification of beaches and coasts, coastal accretion, coastal erosion, beach gradient and profile, historical data on coastal change, and a final chapter on coastal types and developments.

Throughout, the emphasis is on underlying mechanisms and the approach is quantitative wherever this is possible. Full consideration is given to the practical problems of coastal control. The exposition is, on the whole, clear and is helped by numerous line diagrams and maps of good quality. There are no plates.

The book is a detailed survey of a rather narrow geomorphological field and will need no recommendation to those who work in that or in adjacent fields. To the large number of geologists whose interest in geomorphological work is of a general nature, parts of the book will be of minor interest only. Other parts, however, such as those dealing with experiments and measurements of sediment transport, have obvious relevance to many geological problems and will be read with profit. In addition, the book synthesises a large amount of recent work and will be welcomed by many non-specialists on that account alone.

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